Ontario

Ministry of
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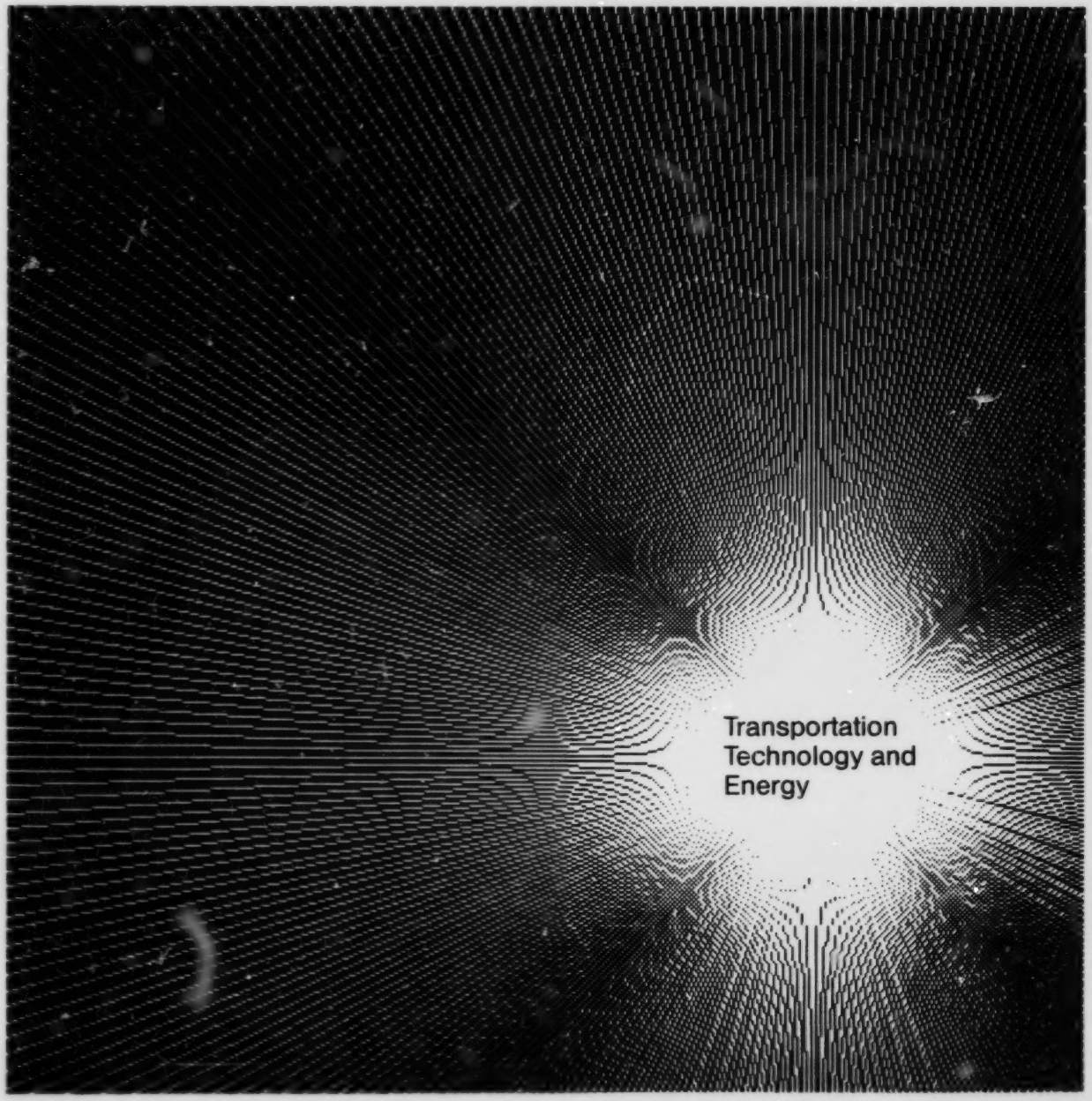
Ride Quality of Ontario Northland TEE-Car and GO Transit Single and Bi-Level Cars

TT-UR-84-01



Technical Report Documentation Page

MTC Report Number	ISBN Number:	Other Document Number:	Date:
TT-UR-84-01			Nov/84

Title: Ride Quality of Ontario Northland TEE-Car and GO-Transit Bi-Level Cars

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Published by:

Transportation Technology and Energy Branch, MTC

Client Group:

Ontario Northland Transportation Commission (ONTC)

Participating Agencies:

ONTC, GO-Transit

Abstract:

Ride quality testing was performed on three rail cars -- the ONTC TEE-train, GO-Transit single level, and GO-Transit bi-level cars -- to determine their relative ride characteristics. Accelerometer signals were recorded aboard the cars over three different track types (differing ride characteristics). These signals were then processed and an ISO analysis performed to determine the "Reduced Comfort" ride quality for different positions in each test car over each piece of test track. Two British Rail ride meters were operated to provide reference information.

A detailed mode shape analysis was also performed on the bi-level car only to investigate upper deck dither.

Key Words: ride quality, ride meter, bi-level, TEE, GO-Transit, accelerometer, ISO, dither, mode shape

Comments:

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Transportation Technology and Energy Branch
Ontario Ministry of Transportation and Communications
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The Editor, Technical Publications
Ministry of Transportation and Communications
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8
(416) 248-7226
June 1984

TABLE OF CONTENTS

	PAGE
List of Tables and Figures	iii
Acknowledgements	v
Executive Summary	vi
1/ INTRODUCTION	1
2/ OBJECTIVES	2
3/ TESTING AND DATA ANALYSIS	3
3.1/ Test Vehicles	3
3.2/ Test Sections	3
3.3/ Instrumentation	4
3.3.1/ Transducers.	4
3.3.2/ Test Equipment	4
3.3.3/ Transducer Mounting.	4
3.4/ Data Acquisition	5
3.4.1/ Tape Recording	5
3.4.2/ Chart Recording.	5
3.5/ Test Procedure	5
3.6/ Data Analysis	6
4/ RESULTS	8
4.1/ British Rail Ride Index	8
4.2/ Time Histories	9
4.3/ ISO Ride Quality	10
4.4/ Power Spectral Density Analysis	11
4.5/ Mode Shapes	12
5/ RIDE QUALITY SPECIFICATION	14
5.1/ Ride Acceptability	14
5.2/ Analysis of the Vertical rms Acceleration Spectra	14
5.3/ Development of Vertical Ride Quality Specification	15
5.4/ Development of Lateral Ride Quality Specification	16
6/ CONCLUSIONS	18
7/ RECOMMENDATIONS	19
8/ REFERENCES	20
APPENDIX A/ ONR Curved Track Characteristics	81
APPENDIX B/ Vertical Ride Acceptability.	82
APPENDIX C/ Lateral Ride Acceptability	85

LIST OF TABLES

PAGE

1/ Test Equipment. 21
2/ Track Characteristics 22
3/ Track Breakdown by Type 22
4/ Interpretation of Ride Index 23

LIST OF FIGURES

1/ Test Locations on ONR Track 24
2/ Transducer Locations for the Bi-Level Car 25
3/ Transducer Locations for the Bi-Level Car (cont'd). 26
4/ Transducer Locations for the GO Single-Level Car 27
5/ Transducer Locations for TEE Car No. 1987-A 28
6/ Layout and Dimensions of GO Bi-Level No. 2150 29
7/ Layout and Dimensions of ONR TEE and GO Single-Level Cars 29
8/ Diagram of the Instrumentation Setup for Analysis 30
9/ British Rail Ride Meter Peak and Average Output 31
10/ British Rail Ride Meter Peak and Average Output 32
11/ British Rail Ride Meter Peak and Average Output 33
12/ Lateral British Rail Ride Index Percentage Exceedance Curves . . 34
13/ Vertical British Rail Ride Index Percentage Exceedance Curves. . 35
14/ Typical Acceleration Time Histories, Curved Track, Bi-Level Car. 36
15/ Typical Acceleration Time Histories, Good Tangent, Bi-Level Car. 37
16/ Typical Acceleration Time Histories, Fair Tangent, Bi-Level Car. 38
17/ Typical Acceleration Time Histories, Curved Track, Single-Level Car (Accn's in m/s^2). 39
18/ Typical Acceleration Time Histories, Good Tangent, Single-Level Car (Accn's in m/s^2). 40
19/ Typical Acceleration Time Histories, Fair Tangent, Single-Level Car (Accn's in m/s^2). 41
20/ Typical Acceleration Time Histories, Curved Track, ONR 'TEE" Car (Accn's in m/s^2) 42
21/ Typical Acceleration Time Histories, Good Tangent, ONR 'TEE' Car (Accn's in m/s^2) 43
22/ Typical Acceleration Time Histories, Fair Tangent, ONR 'TEE' Car (Accn's in m/s^2) 44
23/ ISO Reduced Comfort Boundaries 45
24/ Vertical Acceleration Spectra (Curved Track) 46
25/ Vertical Acceleration Spectra (Good Tangent) 47
26/ Vertical Acceleration Spectra (Fair Tangent) 48

LIST OF FIGURES (cont'd)

PAGE

27/ Lateral Acceleration Spectra (Curved Track) 49
28/ Lateral Acceleration Spectra (Good Tangent) 50
29/ Lateral Acceleration Spectra (Fair Tangent) 51
30/ Vertical Ride Quality 52
31/ Lateral Ride Quality 53
32/ Vertical Acceleration Spectra Bi-Level Car (Curved Track) . . . 54
33/ Vertical Acceleration Spectra Single-Level Car (Curved Track) . 55
34/ Vertical Acceleration Spectra ONR 'TEE' Car (Curved Track). . . 56
35/ Vertical Acceleration Spectra Bi-Level Car (Good Tangent) . . . 57
36/ Vertical Acceleration Spectra Single-Level Car (Good Tangent) . 58
37/ Vertical Acceleration Spectra ONR 'TEE' Car (Good Tangent). . . 59
38/ Vertical Acceleration Spectra Bi-Level Car (Fair Tangent) . . . 60
39/ Vertical Acceleration Spectra Single-Level Car (Fair Tangent) . 61
40/ Vertical Acceleration Spectra ONR 'TEE' Car (Fair Tangent). . . 62
41/ Lateral Acceleration Spectra Bi-Level Car (Curved Track). . . . 63
42/ Lateral Acceleration Spectra Single-Level Car (Curved Track). . 64
43/ Lateral Acceleration Spectra ONR 'TEE' Car (Curved Track) . . . 65
44/ Lateral Acceleration Spectra Bi-Level Car (Good Tangent). . . . 66
45/ Lateral Acceleration Spectra Single-Level Car (Good Tangent). . 67
46/ Lateral Acceleration Spectra ONR 'TEE' Car (Good Tangent) . . . 68
47/ Lateral Acceleration Spectra Bi-Level Car (Fair Tangent). . . . 69
48/ Lateral Acceleration Spectra Single-Level Car (Fair Tangent). . 70
49/ Lateral Acceleration Spectra ONR 'TEE' Car (Fair Tangent) . . . 71
50/ Truck Vertical Acceleration Spectra Bi-Level Car. 72
51/ Bi-Level Longitudinal Modeshapes. 73
52/ Bi-Level Longitudinal Modeshapes. 74
53/ Bi-Level Transverse Modeshapes. 75
54/ Definition of Ride Acceptability Factor 76
55/ ISO 2631 Vertical Ride Acceptability Factor for Toronto - Kapuskasing 77
56/ ISO 2631 Lateral Ride Acceptability Factor for Toronto - Kapuskasing 77
57/ ISO Vertical Ride Quality 78
58/ Minimum Vertical Ride Acceptability (Per Ride Quality Specification) 79
59/ Recommended ISO Ride Specification 80

ACKNOWLEDGEMENTS

The authors would like to thank the Toronto Transit Commission (TTC) and Can Car Rail Inc. for the use of their ride meters in this test. Thanks also go to the management of the Ontario Northland Transportation Commission (ONTC) for making this test possible by arranging the use of the GO Transit single and bi-level cars, supplying the TEE-Train, and for providing all support personnel.

EXECUTIVE SUMMARY

This report documents the ride quality testing performed on three rail-cars:

- ONTC's "TEE-Train", No. 1987-A;
- GO Transit's Bi-Level, No. 2150; and
- GO Transit's Single-Level, No. 1150.

The testing was carried out on three separate sections of ONR track comprising:

- one smooth tangent section -- 113 km/h (70 mph) maximum speed,
- one fair tangent -- 113 km/h (70 mph), and
- one curve -- 64 km/h (40 mph).

Testing was performed during the week of January 16, 1984. Each car was measured for ride quality in the vertical and lateral directions, first in the forward end over the truck centre, and then at the centre of the car (upper and lower decks on the bi-level). The test runs over each of the selected track sections were repeated a minimum of three times.

The test instrumentation included two British Rail ride meters, one Bruel & Kjaer ISO ride meter, six accelerometers mounted on the car floor, and two accelerometers fastened to the forward bi-level truck (one on each side). Electrical outputs from this equipment were recorded on paper and magnetic tape for laboratory analysis.

This report discusses the results obtained from the ride meters and accelerometers in some detail, and compares the ride quality of the three cars. An in-depth analysis of the bi-level and TEE cars is performed which includes much supplementary investigation into the bi-level "dither" problem.

The results may be briefly summarized as follows:

- All cars performed very similarly in the vertical direction on all track sections. The one exception was the bi-level upper deck which performed relatively poorly.

- The TEE and GO single-level cars performed much the same in the lateral direction. The GO bi-level car provided far superior performance relative to the other two cars on all test sections.

- A significant component of the bi-level upper deck dither problem appears to be "drumming". This component had not been identified previously and indications are that stiffening the upper deck or providing more structural damping may significantly improve ride quality at this location. Truck modifications do not appear to be necessary.

The report also develops a ride quality specification to be used by ONR in the purchase of new bi-level equipment. The specification recommends the following:

- Lateral -- A minimum 8 h ISO level must be obtained at any position in the car.
- Vertical -- A minimum 6 h ISO level must be obtained below 5 Hz and 8 h ISO above 5 Hz at any position in the car.

Currently, the upper deck of the bi-level car is the only location which does not meet the recommended specification.

1/ INTRODUCTION

The Ontario Northland Transportation Commission (ONTC) currently provides daily passenger train service between Toronto and the northern Ontario cities of Kapuskasing and Timmins. The "Northlander" service operates on the Toronto-Timmins route. Each day one train leaves from each city, using equipment formerly employed on the famous Trans-European Express service (TEE-Trains). On the Toronto-Kapuskasing service, which ONTC calls "The Northland", the Commission uses trains of domestic design. Each day one "Northland" train leaves Toronto and Kapuskasing.

The domestic Northland is the older of the two train types and the ONTC is currently investigating their replacement with new equipment. One potential replacement for the Northland is the bi-level passenger car, suitably modified, manufactured by Can Car Rail Inc. in Thunder Bay and operated by GO Transit.

In order to compare the bi-level car to their current equipment (TEE) and other single-level technology (a GO single-level car also manufactured by the Can Car plant), the ONTC requested comprehensive ride quality testing of the three cars. The testing was carried out by the Transportation Technology and Energy Branch of the Ministry of Transportation and Communications. This report describes the tests, data analysis, results and conclusions; it also presents a ride quality specification recommended for the new cars to be acquired by the ONTC.

The track has a significant influence on the ride quality and as a result the ONTC identified three sections of track, north of North Bay, which would be somewhat representative of the variety of track conditions and geometry found on the above-mentioned runs. The three sections comprise representative examples of:

- good tangent track,
- fair tangent track, and
- a smooth curve.

This enabled the study to include the effects of track condition and geometry on ride for a given vehicle.

2/ OBJECTIVES

The following objectives were set for the test program:

1/ To quantify the ride characteristics of the TEE-Train, GO single-level and bi-level cars over three ONR (Ontario Northland Railway) test track sections.

2/ To obtain the data required for the development of a ride quality specification for the ONTC cars.

3/ To study the bi-level dither phenomenon in some detail, under actual operating conditions.

3/ TESTING AND DATA ANALYSIS

3.1/ Test Vehicles

Three passenger cars were tested during the week of January 16, 1984. The following is a description of each:

1/ GO Bi-Level -- The bi-level used was a series II car, #2150, selected as a typical representative of the latest design. This particular car was coupled to the back of a series I bi-level to simulate actual operating conditions.

2/ GO Single-Level -- A typical GO single-level car #1150 was tested. It was coupled to the back of the series II bi-level car. A similar single-level car was connected to the rear of the first.

The first single-level, #1150 was used as the test car and the instrumentation centre which included the signal collection, processing and recording equipment for the testing of the GO single- and bi-level cars.

3/ TEE -- Car A of ONTC's TEE-Train, #1987 was selected. It was the first car of a three car consist and was considered to be typical of its type. This was the identical car that underwent similar testing in November 1983 as documented in Reference 1.

3.2/ Test Sections

The three selected test sections are all within 74 km (46 miles) of the ONTC yard in North Bay (test locations are mapped in Figure 1).

Details of the three test sections are as follows:

1/ Curved -- The curved section consists of a two-mile stretch (from mile post 23 to 25) incorporating six individual curves. The grade on this section is -1%. The track characteristics with respect to curve length, radius and superelevation are given in Appendix A. Speed through this section is limited to 64 to 72 km/h (40-45 mph).

2/ Good Tangent -- this section is a two-mile stretch of continuously welded track from mile post 37 to 39. Typical speeds on this run are 97 to 113 km/h (60 to 70 mph). The grade on this section is +0.24%.

3/ Fair Tangent -- The last section is two miles long from mile post 44 to 46 and is comprised of jointed tracks. Typical speeds are 97 to 113 km/h (60 to 70 mph) and the grade is +0.27%.

3.3/ Instrumentation

3.3.1/ Transducers

The transducers used comprised several accelerometers and ride meters.

Vertical and lateral accelerations at several locations on the car floor were measured using Bruel & Kjaer "Uni-Gain" accelerometers, type 8306. The Bruel & Kjaer "Uni-gain" type 4371 accelerometer was used to measure the truck frame vertical acceleration.

Lateral and vertical British Rail ride indices were measured by means of two Data Acquisition Limited vehicle ridemeters ("Mark II" Model). The Bruel & Kjaer ISO standard Human-Response vibration meter (Model 2512) was also used to measure ride quality. A Bruel & Kjaer type 4322 tri-axial accelerometer was connected to the ISO H-R meter.

3.3.2/ Test Equipment

A complete description of test equipment used during the test is produced in Table 1. It essentially consists of data acquisition, processing and recording apparatus as well as the required power supplies.

3.3.3/ Transducer Mounting

The truck frame vertical acceleration transducers were permanently fastened to the forward truck of bi-level car #2150 during all test runs. All other accelerometers, mounted to heavy steel blocks (approximately 7 kg (15.4 lbs) each), were located in their predetermined positions.

A total of 10 different transducer layouts were utilized between the three test cars. Figures 2, 4 and 5 illustrate the general transducer layouts on all three test cars. Figure 3 gives the accelerometer locations for the "mode shape" testing on the bi-level (this will be discussed in detail later in the report). Figures 6 and 7 provide the general dimensions of the TEE, GO single- and bi-level cars.

3.4/ Data Acquisition

3.4.1/ Tape Recording

The transducer output signals were frequency modulated, multiplexed and recorded on magnetic tape using a Hewlett Packard 3964A recorder. This conversion enabled the storage of up to eight channels on a single track. The above process was reversed in the laboratory for further analysis.

3.4.2/ Chart Recording

During the tests, channels nine through 15 plus the time code were recorded on paper charts using an MFE model 1800 recorder. The charts enabled monitoring of the quality of data being acquired and provided some quick results.

3.5/ Test Procedure

As discussed in Section 3.2, three test sections were chosen on which to monitor the ride quality of the three test cars described in Section 3.1. Test Positions 1, 2 and 3 (Figure 2) and 7 through 10 (Figures 4 and 5) were repeated at least three times over each test section, while "mode determination" positions 4, 5 and 6 (Figure 3) were run only over test section number three (also a minimum of three times per position).

A total of 75 test runs were recorded during the week of testing on the three cars.

3.6/ Data Analysis

Data analysis is initiated with the playback of data, stored on magnetic tape, to the time code reader and a demodulator (See Figure 8). The time code reader gives a continuous display of the time at which the recording was made. The tape position may be related back to actual test time enabling ready access to the appropriate tape sections. The demodulator reconstructs the recorded signals from the tape.

The data was subjected to two different types of analysis: (1) time domain, and (2) frequency domain. A time domain analysis involves routing data from the demodulator to a digitizing system, consisting of a PDP8/A processor combined with a Fairchild F8 microprocessor to start and stop the PDP8 depending upon the time code. The digitized data is then fed into the main data analyser, a Hewlett Packard 9845T computer and analysed. The main outputs of this analysis are time history plots, percentage exceedance curves and rms values.

The frequency domain analyses were performed by processing the data from the demodulator on a Fast Fourier Transform analyser (a Nicolet 660 A dual channel FFT analyser), two channels at a time. The FFT analyser outputs include power spectral densities (PSD) and rms spectra of the two signals and the transfer function (both phase and relative amplitude) between the two signals. The FFT analyser output was fed into the HP9845T computer where all data was converted to engineering units and then properly formatted, stored and plotted.

The rms spectra information may be used to plot (1) narrow band, or (2) one-third octave curves. The difference between the two is in the number of points or "cells" plotted. A one-third octave plot would have points plotted at 13 different cells from 1 to 20 Hz (at one-third octave spacing) whereas the narrow band plot would have 133 points over the same range.

A narrow band representation is typically used to display power spectral density (PSD) information and the one-third octave, rms information.

Mode shape plots are also formulated from the frequency domain information. A plot of relative mode shapes represents the relative signal level at a number of measuring locations on the vehicle at one particular frequency cell. The magnitudes are normalized in relation to a "reference" location. The linear component of the signal with respect to that at the reference location is represented by a line on the plot (line length is proportional to the relative signal ratio). The orientation of the line is represented negatively if the relative phase angle between the point and the reference location falls between 90° and 270° and positive if it falls outside this range.

4/ RESULTS

4.1/ British Rail Ride Index

The average and peak ride indices were computed for each run in both the lateral and vertical directions (using the time domain output). All repetitions on a given test track section with a particular ride meter position were subsequently averaged and plotted in Figures 9, 10 and 11. TEE, GO single- and bi-level averages from the most recent test (January '84) as well as the former (November '83) TEE figures are compared. A smaller ride index corresponds to a better ride. Table 2 gives a description of ride quality corresponding to a range of ride index values.

Several observations may be made with regard to these figures.

1/ The lateral ride quality of the bi-level car is generally better than either the GO single-level or TEE cars on any test track section.
2/ The bi-level vertical ride quality is consistently better on the lower deck than it is on the upper.
3/ The TEE recent and former ride indices are in good agreement with each other suggesting that the test conditions have not significantly changed.
4/ The GO single-level car produces average ride quality indices which are very similar to those of the TEE car.

Another means of presenting the ride quality information is in the form of "percentage exceedance" graphs (see Figures 12 and 13). Each curve represents the percentage of total test time that the ride quality index on the x axis was exceeded. For example, in Figure 12(a) the ride quality of the GO single-level car (evenly broken line) is seen to have the following characteristics:

1/ A ride index above 2.0 was observed 100% of the time.
2/ A ride index above 2.5 was observed approximately 46% of the time.
3/ A ride index above 3.0 was observed less than 10% of the total test time.

A steeper line indicates less variation in ride quality over the test period. Improving ride quality is represented by positioning the line further to the left on the graph.

Note that the lateral performance of the bi-level car is superior to the other two cars on all three types of track. Vertical performance is similar for all three cases shown, independent of track type.

Due to time limitation, the percentage exceedances were determined for one location on each car only.

4.2/ Time Histories

As described in Section 3 of this report, signals from eight accelerometers were recorded in addition to the BR ride indices. The two 4371 type accelerometers were permanently mounted on the front truck of the forward bi-level car -- one on each side, below the air suspension system. The other six accelerometers (Type 8306, mounted on steel blocks) were moved around from position to position (Figures 2 through 5). The electrical output from the accelerometers was recorded during the test on magnetic tape and then reproduced in the laboratory for analysis. This output signal is referred to as a "time history".

Typical acceleration time histories for the three cars have been reproduced in Figures 14 through 22. The figures are divided into groups by car (first three -- GO single-level, second three -- bi-level, last three -- TEE) and by track (first page -- curved, second -- good tangent, third -- fair tangent).

The following may be observed from these figures:

1/ Both the lateral and vertical vibration on the upper deck of the bi-level car is dominated by higher frequencies than is the case with the other two cars.

2/ Acceleration levels at other locations of the bi-level car are relatively small.

3/ The TEE and single-level car motions (both lateral and vertical) are dominated by large low frequency oscillations.

4/ Generally speaking, there is larger vibration on the tangent sections than on the curved sections, presumably because of the higher speed.

5/ It is interesting to note the large vertical response of all three cars on the second half of the good tangent section, presumably due to a track irregularity. Of the cars tested, the TEE car appears to provide the greatest reaction to this irregularity.

4.3/ ISO Ride Quality

A more accurate and comprehensive picture of ride quality than that provided by the British Rail ride index may be obtained with the use of analysis recommended by the International Standards Organization (ISO) in its specification Number 2631 [2].

In order to determine the ISO ride quality, the acceleration signals are first processed (Section 3.6) to determine their rms spectra in one-third octave bands. A typical blank rms acceleration spectrum is shown in Figure 23. The broken lines printed on the spectrum are the ISO "reduced comfort" boundaries, labelled 1 through 24 h. The ride quality measured in ISO hours is determined as the rms value corresponding to the largest peak in the rms spectrum.

Figures 24 through 26 present vertical rms acceleration spectra at various locations on the three cars, over the three test sections. The spectra shown are the averages for the three runs made on each test section. The following observations may be made from these figures:

1/ The bi-level car's upper deck shows a large peak in the high frequency range. The peak is at 12 Hz on the two tangent sections and at 16 Hz on the curved sections.

2/ The ride quality on the upper deck of the bi-level car is constantly inferior to that of both other locations on the car by a large margin. It is also worse than the ride quality of the TEE and single-level cars.

3/ The vertical vibration on all three cars shows two peak regions. The lower frequency peaks are in the 1 - 3 Hz range while the higher frequency peaks are in the 10 - 16 Hz range.

4/ The largest peak in the low frequency range generally occurs above the front truck, while in the high frequency range it occurs at the centre of the car.

Figures 27 through 29 show the lateral rms acceleration spectra. The following general trends are observed from these figures.

1/ On the bi-level car, the vibration levels are extremely small in the low frequency range (0 - 5 Hz). The ride quality is thus dictated by the components above 5 Hz.

2/ The upper deck on the bi-level car constantly displays larger vibration than on the lower deck, which in turn displays larger vibration than the intermediate deck.

3/ Both the GO single-level and TEE car spectra are dominated by the low frequency (0 - 5 Hz) components and give a significantly worse lateral ride than the bi-level car.

From the Figures 24 through 29, the ISO ride quality hours are determined for each car on each test section. The vertical ride quality results are illustrated in Figure 30 while the lateral ride quality is shown in Figure 31. Note that with the ISO analysis, a better ride is associated with a greater ISO hour figure, unlike the BR ride meter. From Figure 30, it can be clearly seen that the vertical ride on the upper deck of the bi-level car is inferior not only to the other locations on the same car, but to the other two cars as well. At the centre of the lower deck and above the front truck, the vertical ride quality is generally superior to that at similar locations on the other two cars.

From Figure 31, it is clear that the lateral ride at all locations on the bi-level car is far superior to that on the other two cars.

4.4/ Power Spectral Density Analysis

A convenient means of presenting the vibration energy level as a function of frequency (for each test) is the "power spectral density", or PSD plot. Examples of PSD's from the January 1984 tests are given in Figures 32 through 49 for car body locations and Figure 50 for truck mounted positions.

There are two main distinctions between the PSD's presented here and the rms spectra presented in Section 4.3. The former are narrow band spectra while the latter are one-third octave spectra. Thus, the former have a much higher frequency resolution and therefore various resonant frequencies may be determined more easily from the PSD's. Also, the PSD is a density function with units of mean square value/Hz. Thus, the mean square acceleration in any frequency band is equal to the area under the PSD curve within that band. In contrast, the rms spectra presented show the rms value in each one-third octave frequency band at its centre frequency. (Note than an octave band represents a frequency ratio of 2, i.e., its upper frequency limit is twice the lower frequency limit. A one-third octave band has a frequency ratio of $2^{1/3}$ or 1.260.)

The wheel rotational frequencies are illustrated in the PSD plots for the bi-level truck (Figure 50). Note that the truck vibration indicates a hump centred approximately on the wheel rotational frequency. These also appear to shift together with changing vehicle speed and there is no clear evidence of truck heave or pitch frequencies on these graphs.

4.5/ Mode Shapes

A rail vehicle is a complex dynamic system with a large number of "modes" of vibration. A simple mode may consist of motion of a single body in one direction only, for example, up and down motion of the car body. However, in practice, each mode is quite complex consisting of several motions in different proportions and phase relationships. The shape function that depicts the relationship between various motions is referred to as the "mode shape". This concept becomes clearer when some examples are seen later in this section. As described in Section 3, the bi-level car mode shapes were determined by simultaneously measuring vertical accelerations at several locations on the car. The mode shape determination was carried out to give an improved understanding of the "dither" phenomenon.

The accelerometer arrangements used for mode shape determination are described in Section 3.3.3 and shown in Figure 3. The procedure used for determining the mode shapes is described in Section 3.6. In this report,

mode shapes are presented for frequencies between 10 and 17 Hz only, as this was found to be the frequency range of dither.

Figures 51 and 52 show the longitudinal mode shapes at eight different frequencies. Figure 53 depicts transverse mode shapes at these same frequencies. The top arrows represent the roof-mounted accelerometers, the centre arrows the upper deck and the lower arrows the lower deck. Again the length of the arrow is a function of the energy at that location relative to the reference accelerometer on the centre of the upper deck.

Figures 51 and 52 show the presence of body heave, bending and upper deck drumming. The relatively small displacements on the intermediate deck show the heave component while the variation in amplitude along the lower deck, with maximum deflection at the centre shows body bending. In addition to the above, the upper deck appears to have a significant "drumming" component (i.e., two dimensional deflection) as evidenced by Figures 51 through 53. The drumming component, while evident at all frequencies becomes more and more pronounced as frequency is increased. The presence of the large drumming component suggests that the upper deck structure is of insufficient rigidity.

If it is possible to virtually eliminate drumming, the ride quality on the upper deck can be improved to match that of the lower deck level. Two approaches may be used to reduce drumming -- the upper deck structure may be made more rigid or adequate structural damping may be provided. In either case, established structural dynamic test techniques may be used to verify the adequacy of design changes, or even in arriving at the most effective design change, well before committing a large amount of funds.

5/ RIDE QUALITY SPECIFICATION

5.1/ Ride Acceptability

The ISO ride quality figures from Section 4.3 form the basis of the ride quality specification development for a rail vehicle travelling from Toronto to Kapuskasing. On such a trip, the passenger is exposed to a different quality of ride over each different section of track. As illustrated in Figure 54, the trip ride characteristic may be represented by ISO ride quality figures τ_i corresponding to trip times t_i. Using the simple equation, provided in the same figure, the "ride acceptability factor" (RAF) may be determined for the entire trip. An RAF greater than or equal to 1 means that the ride quality is acceptable; less than 1 is unacceptable.

Ride acceptability factors have been calculated (Appendix B) and illustrated in Figures 55 (vertical) and 56 (lateral) according to the recommended ISO procedure [2]. Note that the bi-level car has acceptable lateral ride at all locations, while the vertical ride is acceptable at all locations except the upper deck.

5.2/ Analysis of the Vertical rms Acceleration Spectra

The vertical rms acceleration spectra presented in Figures 24 through 26 are discussed in detail in Section 4.3. In particular, it was observed that the vertical vibration plots for each of the three cars form two peaks -- one in the 1 - 3 Hz range and the second in the 10 - 16 Hz range.

It was therefore felt that it would be useful to determine the ride quality separately for frequencies below and above 5 Hz. The results of such analysis are shown in Figure 57 and summarized below:

Below 5 Hz

- On the curved track, the bi-level car has a somewhat worse ride than the TEE but it is more than satisfactory at a minimum of ISO 15 h level.

- On both good and fair tangent sections, the ride quality at all locations of the bi-level car exceeds that on the TEE car and has a minimum of ISO 6 h level. This level is shown in Figure 57 for reference.

Above 5 Hz

- The ride quality at the centre of the upper deck is consistently poor and always worse than that on the TEE car. At the two other locations on the bi-level car, the ride quality is equal to or better than the ISO 8 h level.

5.3/ Development of Vertical Ride Quality Specification

In the preceding section quantitative measurements have been presented, compared and discussed. Now it is necessary to develop ride specifications for the ONR bi-level cars. The following considerations are used in the development of the specifications:

1/ The ride quality at any point on the bi-level car should be equal to or better than that on the present TEE cars.

2/ The ride on the entire Toronto-Kapuskasing run should ideally not lead to "reduced comfort" as defined in the ISO specification [2].

3/ The specified ride quality should be achievable within the current state of the art.

4/ The authors feel, based on subjective observations that the same amount of dither can be more annoying on the bi-level car than on the TEE car. It appears that, in the absence of significant vibration at other frequencies, the passenger's attention is drawn more sharply to the dither. This theory is also supported by Kauffman [3]. As a result, the dither component on the bi-level car should be brought to a significantly lower level than that on the TEE car.

Application of the above criteria together with the results presented in Section 5.2 lead to the following recommendation for vertical ride in the bi-level car.

- Below 5 Hz, the vertical ride quality shall have a minimum value of 6 h on the ISO "Reduced Comfort" scale.
- Above 5 Hz, the bi-level shall have a minimum vertical ride quality of 8 h on the ISO "Reduced Comfort" scale.

The above two requirements shall be met at all locations on the car, on all ONR track sections and at all operating speeds.

The first requirement is met by the present bi-level car. Since the worst ride quality below 5 Hz occurs in the intermediate level above the trucks, any improvement beyond the 6 h level would be difficult. The authors feel that no such improvement is necessary.

The second requirement above requires that the ride quality on the bi-level car, above 5 Hz, be much better than that on the TEE car. The rationale for this is based upon criterion 4 above. As the present ride quality on the lower deck is at the 8 h level, the suggested requirement is considered realistic, i.e., it satisfies criterion 3 above.

While the manufacturer may be requested to aim higher, it is not considered advisable to make the specification more stringent.

Note that the above two requirements specify improvements to the present bi-level car in one area only, viz, the ride quality on the upper deck in the high frequency range. In formulating these two requirements, the authors assumed that this improvement will not affect the ride quality at other locations or at any location in the low frequency range.

Ride acceptability factors for a hypothetical car that just meets the above requirements are calculated in Appendix B. As shown in Figure 58, the specified requirements lead to an acceptable ride at all test locations on the bi-level car.

5.4/ Development of Lateral Ride Quality Specification

Lateral acceleration data was processed in a manner similar to that described in Section 5.2. The ISO lateral rms spectra are reproduced in

Figures 27 through 29 and the average lateral ISO 'Reduced Comfort' hours are illustrated in Figure 31 for the TEE, GO single- and bi-level cars. The bi-level ride is clearly superior to that of the TEE car in every case. Lateral ride acceptability calculations for the TEE and bi-level cars are given in Appendix C and the results are shown in Figure 56. As shown, the lateral ride on the bi-level car meets the ISO requirements while the TEE car does not.

While the present bi-level car has a minimum ride quality of 8 h, it is felt that a 6 h ride quality is sufficient to give acceptable ride. Appendix C also examines the ride acceptability with the 6 h requirement. The specified minimum ride acceptability factors have been marked on Figure 56 to illustrate the difference between the current bi-level and TEE car figures. While the ride acceptability factor falls slightly short of the desired minimum value of 1 on the upper deck of the bi-level, it is considered desirable to specify the 6 h requirement for the following reasons:

1/ Even at the 6 h level, the bi-level car lateral ride will be far superior to the TEE car.

2/ The 6 h requirement, which is below the current performance of the bi-level car, might give some leeway to the manufacturer in making design changes to improve the vertical ride.

3/ The 2 h margin will allow for any variability between cars.

In view of the above, the following specification is recommended:

The lateral ride quality of the ONR bi-level car must therefore have a minimum value of 6 h on the ISO "Reduced Comfort" scale. This requirement shall be met at all locations on the car, on all ONR track sections and at all operating speeds.

6/ CONCLUSIONS

The ride quality of the GO bi-level, single-level and ONTC TEE-Train cars has been tested in detail over three representative sections of ONR track. In general, the bi-level car met the ISO requirement for ride acceptability on the Toronto-Kapuskasing trip -- in the lateral direction at all in-car locations and in the vertical direction, everywhere but at the centre of the upper deck. In addition, the car performed as well as, or better than, the TEE car at all locations but this one. In order to meet the ISO vertical ride acceptability requirements on the upper level, the bi-level car must attain a minimum 8 h ISO ride quality figure above 5 Hz.

The detailed mode shape analysis yielded some interesting results, particularly in the description of the upper deck bi-level vibration. While evidence of car body bending and heave is apparent in the longitudinal axis, there exists a predominant upper deck "drumming" phenomenon especially above 13 Hz. This finding suggests that the "dither" problem may be one of inadequate upper deck stiffness.

The ride analysis performed on the three rail cars provides much information detailing the observed ride performance as well as providing some insight into their relative strengths and deficiencies. Hopefully, the analysis has not only produced a ride quality specification for ONTC but also provided much useful information on the car ride characteristics in general.

7/ RECOMMENDATIONS

1/ It is recommended that the ride quality specification for the bi-level equipment be adopted by ONTC as described in Sections 5.3 and 5.4 of the report for the purchase of new equipment.

2/ The mode shape analysis, part of which is contained in this report, should be reviewed by the bi-level equipment manufacturer to aid in the understanding of the "dither" problem.

8/ REFERENCES

[1] "Ride Quality of Ontario Northland Rail Car, #1987-A," Ministry of Transportation and Communications, Report #VS-84-01.

[2] "Guide for the Evaluation of Human Exposure to Whole Body Vibration," International Standard #2631.

[3] Koffman, J.L., "The Connection Between Coach Body and Bogies," Rail Engineering International, February/March 1972.

Table 1/ Test Equipment

Item	Equipment	Car Type
1	Metraplex "300 series" signal conditioning/FM data acquisition system	all cars
2	Hewlett Packard Model 3964A instrumentation recorder	all cars
3	MFE Model 1800 8-channel chart recorder	all cars
4	On board 120 Vac, 60 Hz power supply	GO cars #2150 & #1105
5	On board 220 Vac, 50 Hz power supply	TEE #1987-A
6	Hewlett Packard Model 6269-B dc power supply	TEE #1987-A
7	Honeywell Model DA12-A electric generator	TEE #1987-A

Table 2/ Track Characteristics

Track Section	Approximate Distance by Track - km (mi)
Kapuskasing - Cochrane (CNR)	113 (70)
Cochrane - Porquis Jct (ONR)	48 (30)
Porquis Jct - North Bay (ONR)	362 (225)
North Bay - Toronto (CNR)	367 (228)
Kapuskasing - Toronto (Total)	890 (553)
Total CNR	480 (298)
Total ONR	410 (255)

Table 3/ Track Breakdown by Type

Track Type	Approximate Distance - km (mi)
Curved	356 (221)
Good Tangent	178 (111)
Fair Tangent	356 (221)
Total	890 (553)

Table 4/ Interpretation of Ride Index*

RIDE INDEX		QUALITY OF RIDE
1.0	--	Very good
1.5	--	Almost very good
2.0	--	Good
2.5	--	Almost good
3.0	--	Satisfactory
3.25	--	Satisfactory with limitations
3.5	--	Just satisfactory
4.0	--	Operable
4.5	--	Not operable
5.0	--	Dangerous

* Ref. Instruction Manual, Ridemeter MKII.

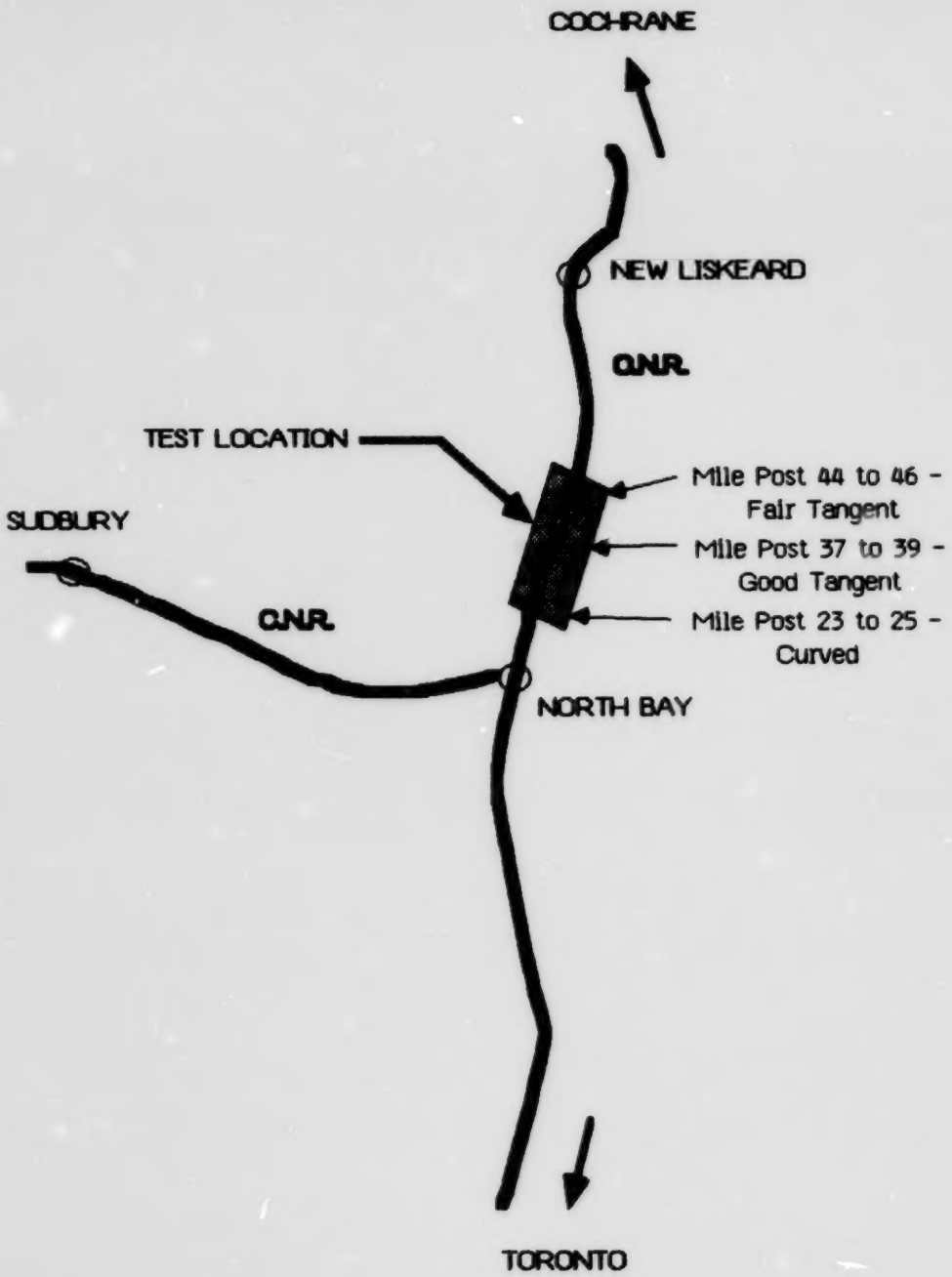
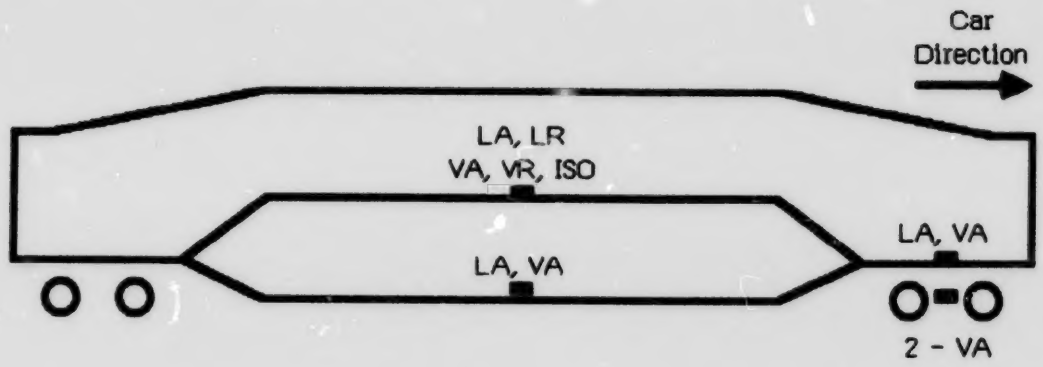
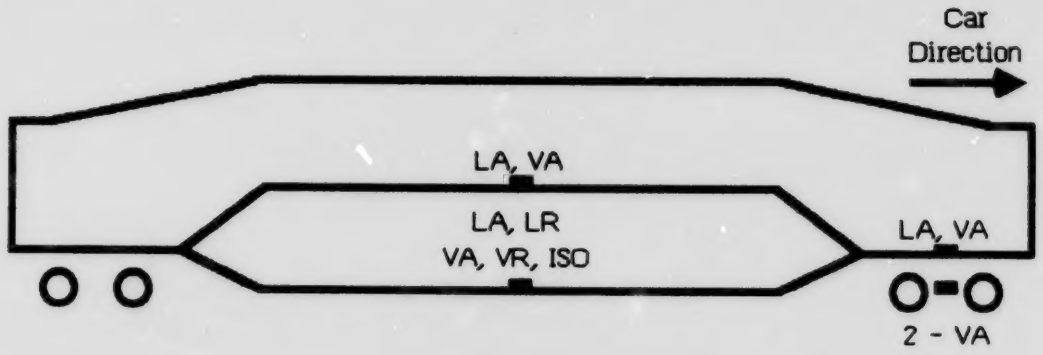


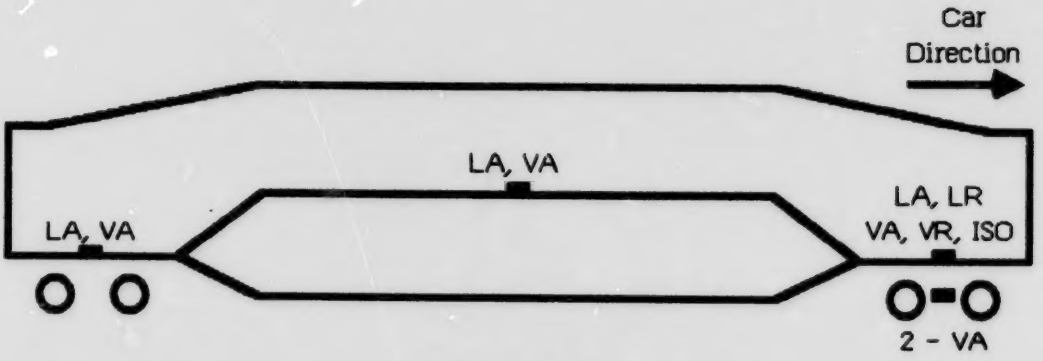
Figure 1/ Test Locations on ONR Track



(a) POSITION 1



(b) POSITION 2

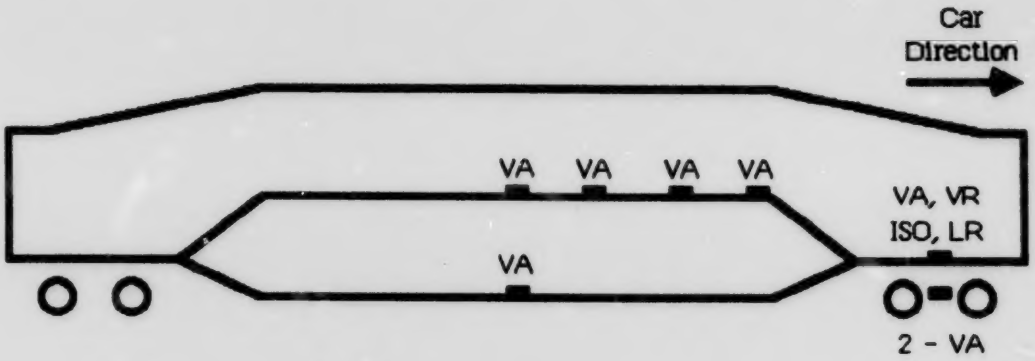


(c) POSITION 3

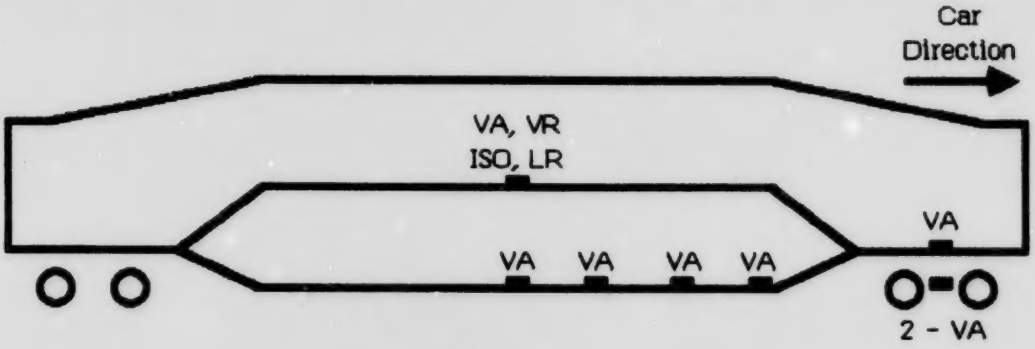
L - Lateral
A - Accelerometer
V - Vertical

R - Br Ride Meter
ISO - B & K ISO Ride Meter

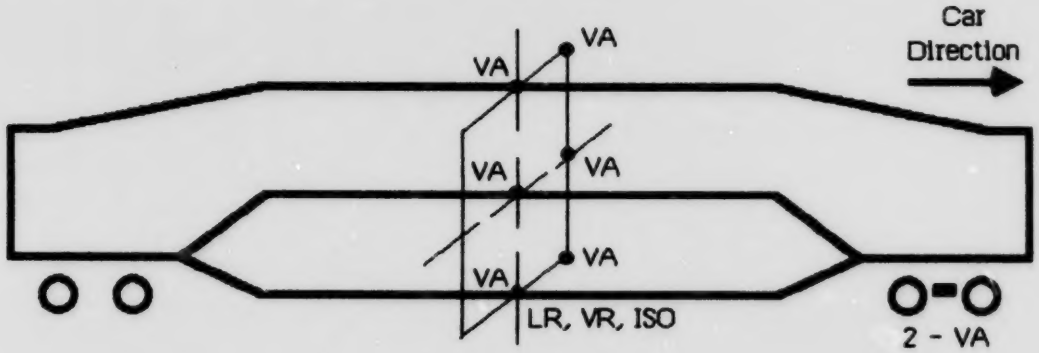
Figure 2/ Transducer Locations for the Bi-Level Car



(a) POSITION 4



(b) POSITION 5

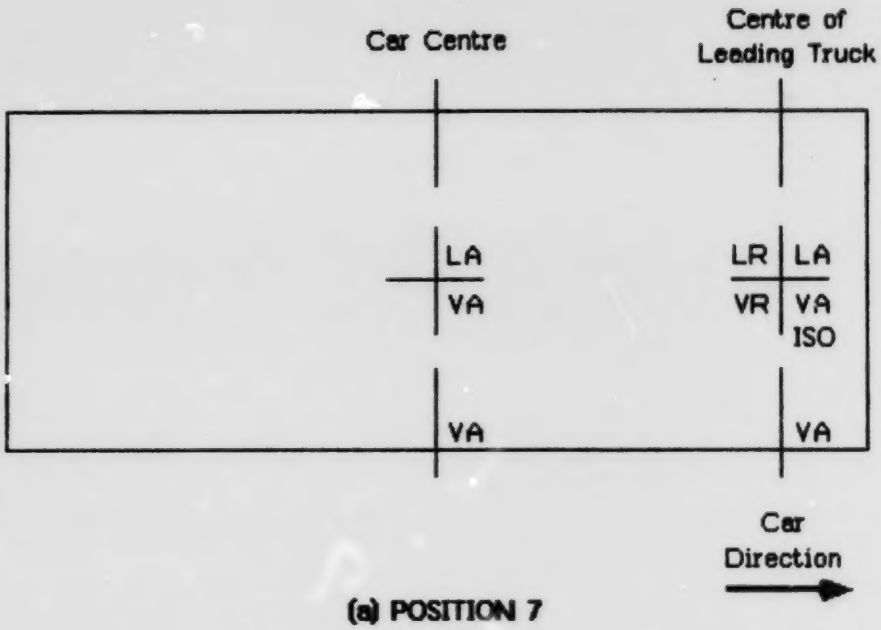


(c) POSITION 6

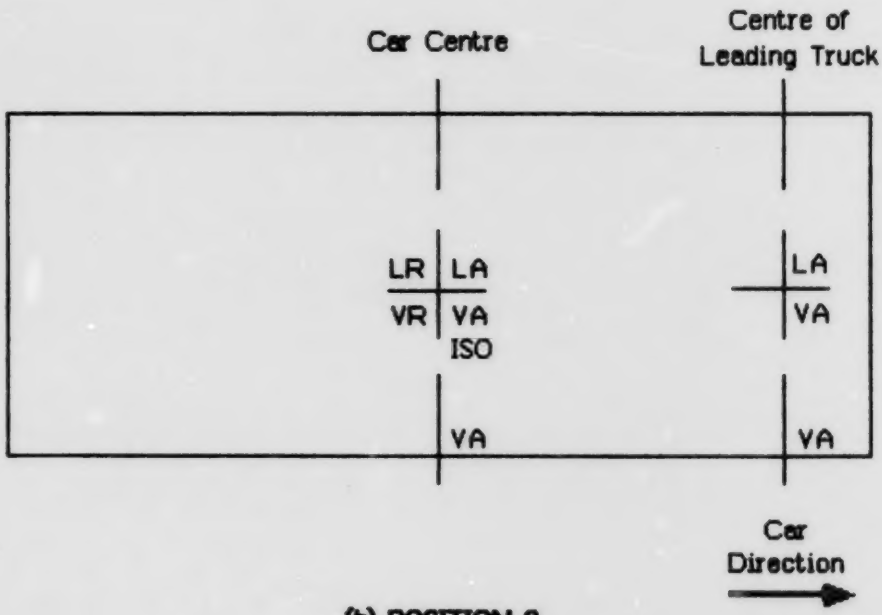
L - Lateral
A - Accelerometer
V - Vertical

R - Br Ride Meter
ISO - B & K ISO Ride Meter

Figure 3/ Transducer Locations for the Bi-Level Car (con't)



(a) POSITION 7

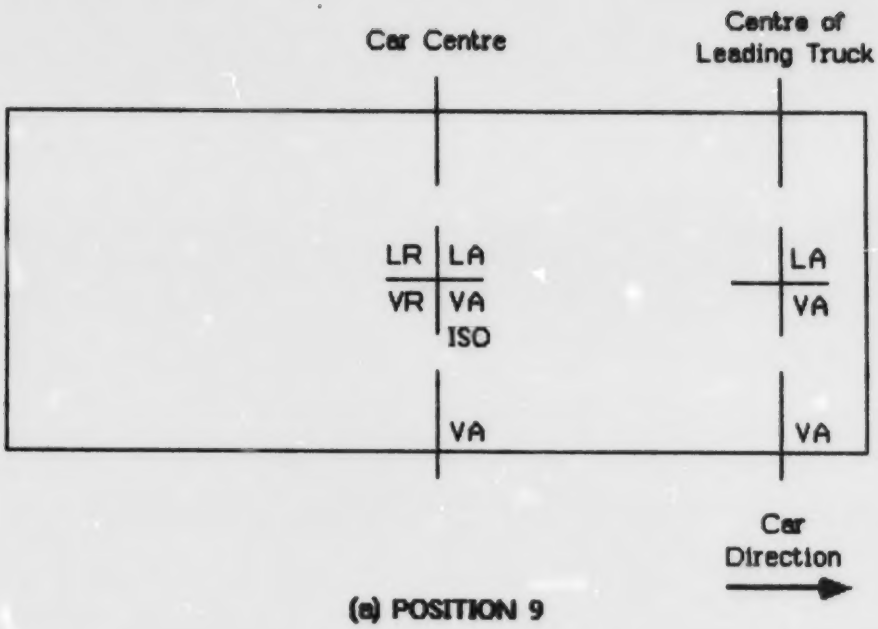


(b) POSITION 8

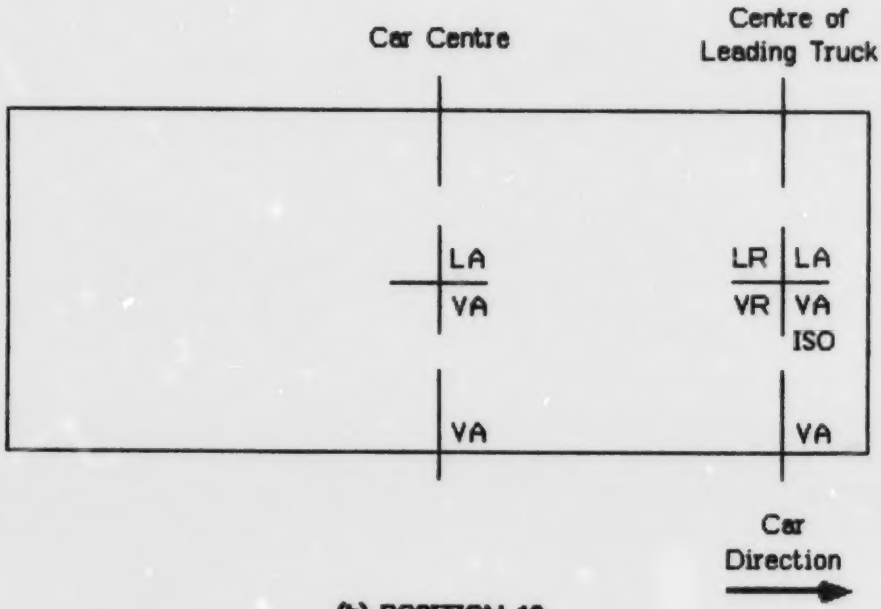
L - Lateral
A - Accelerometer
V - Vertical

R - Br Ride Meter
ISO - B & K ISO Ride Meter

Figure 4/ Transducer Locations for the GO Single-Level Car



(a) POSITION 9



(b) POSITION 10

L - Lateral
A - Accelerometer
V - Vertical

R - Br Ride Meter
ISO - B & K ISO Ride Meter

Figure 5/ Transducer Locations for TEE Car No. 1987-A

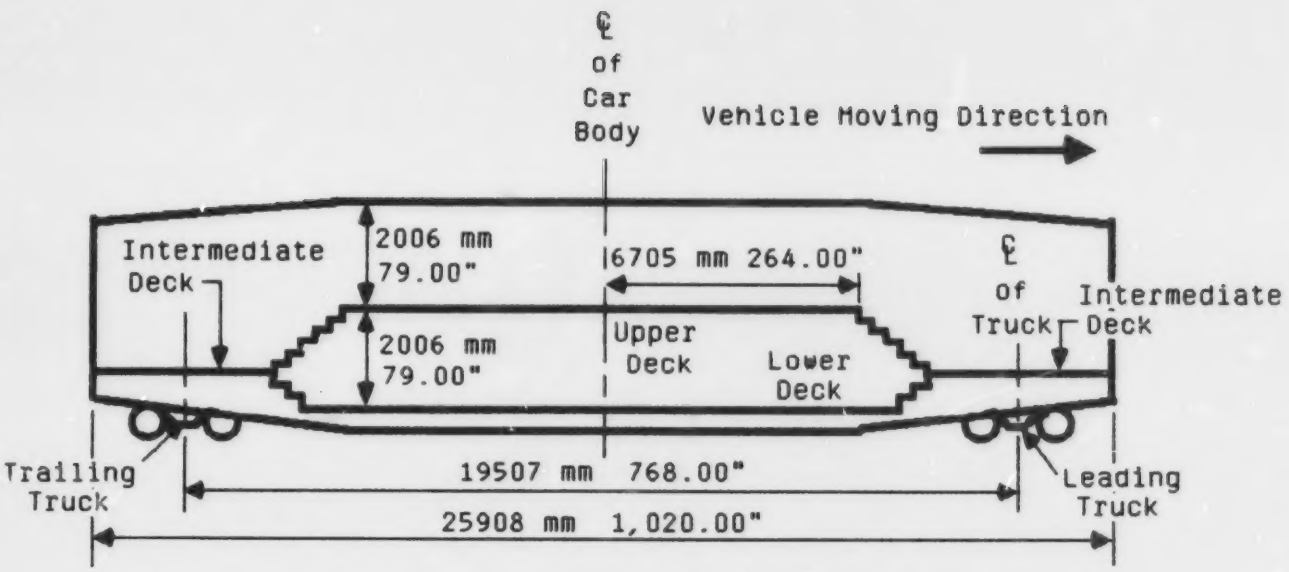


Figure 6/ Layout and Dimensions of GO Bi-Level No.2150

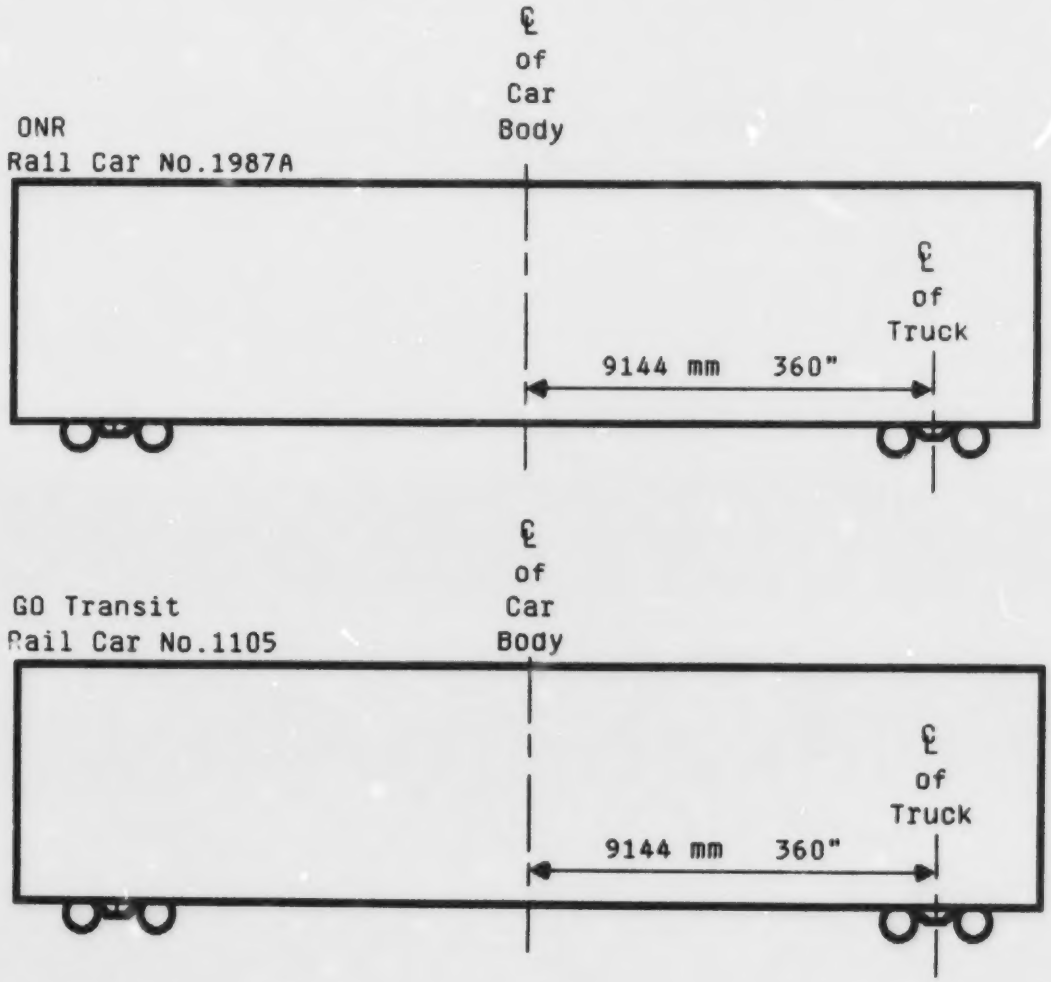


Figure 7/ Layout and Dimensions of ONR TEE and GO Single-Level Cars

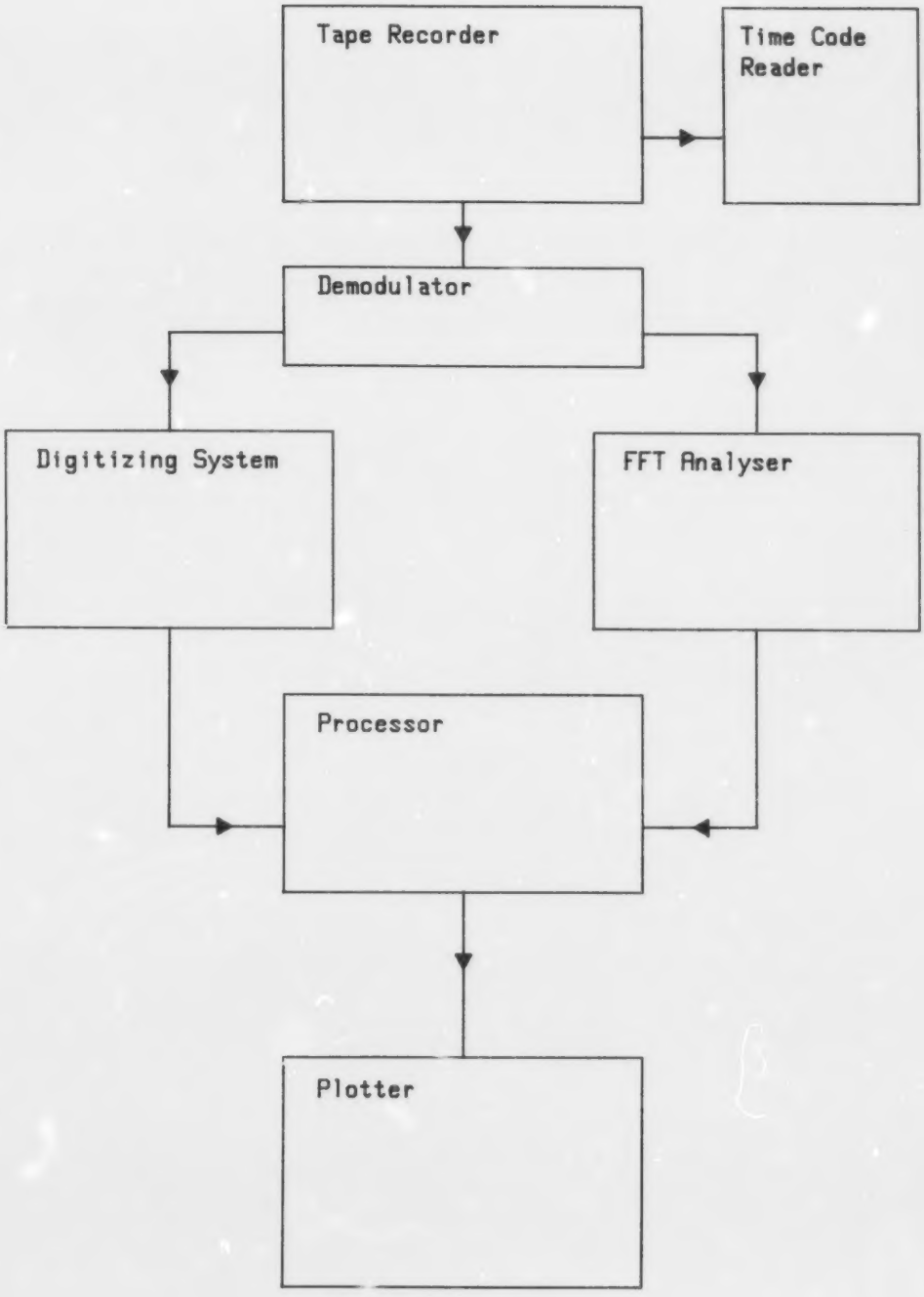
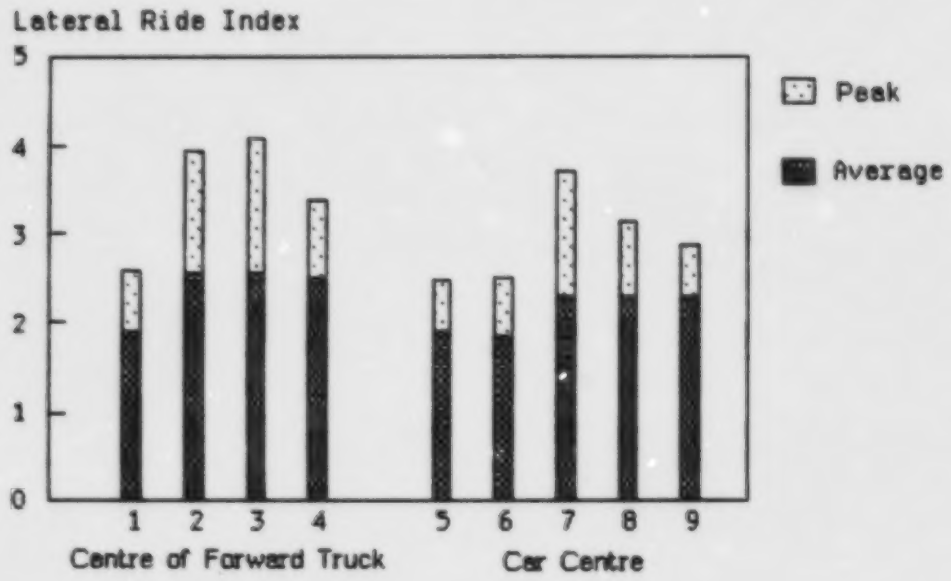


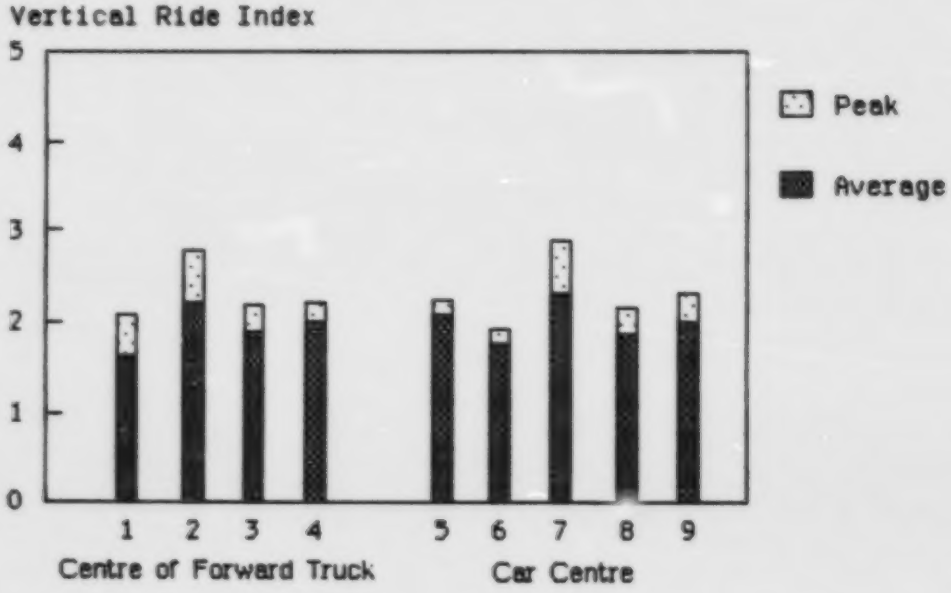
Figure 8/ Diagram of the Instrumentation Setup for Analysis

Test Track Section 1 Curved Track

(a) Lateral



(b) Vertical

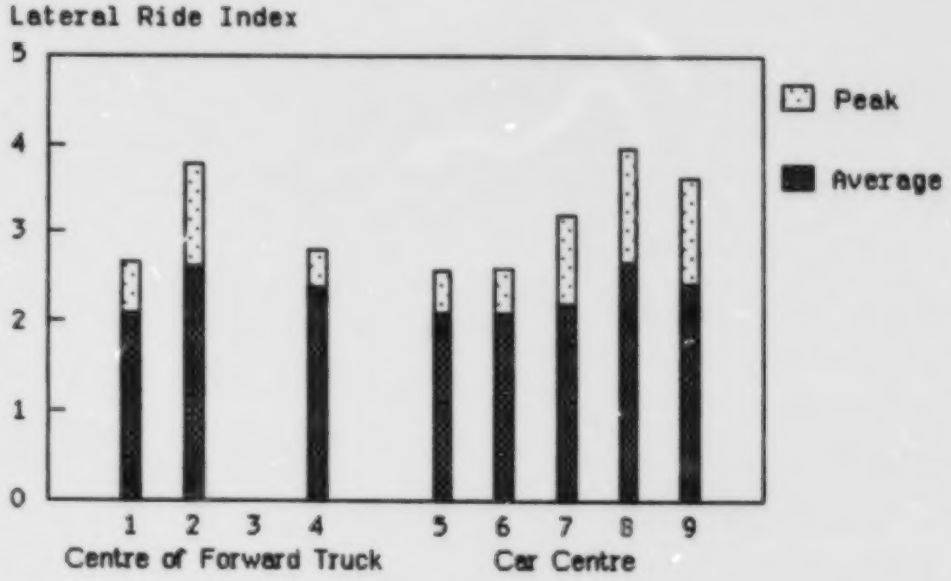


1 - GO Bi-Level
2 - GO Single-Level
3 - TEE Recent
4 - TEE Former
5 - GO Bi-Level Upper
6 - GO Bi-Level Lower
7 - GO Single-Level
8 - TEE Recent
9 - TEE Former

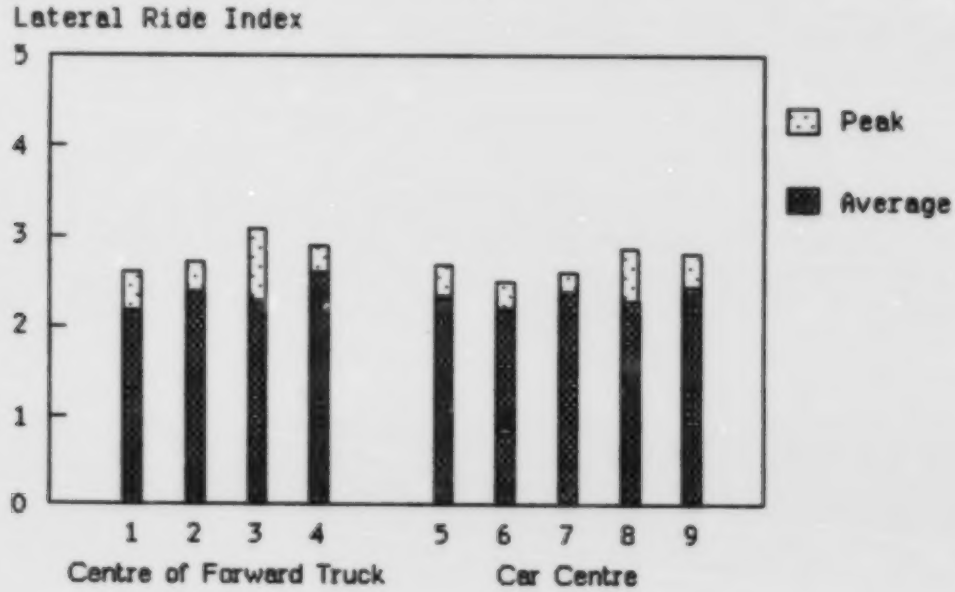
Figure 9/ British Rail Ride Meter Peak and Average Output

Test Track Section 2 Good Tangent

(a) Lateral



(b) Vertical

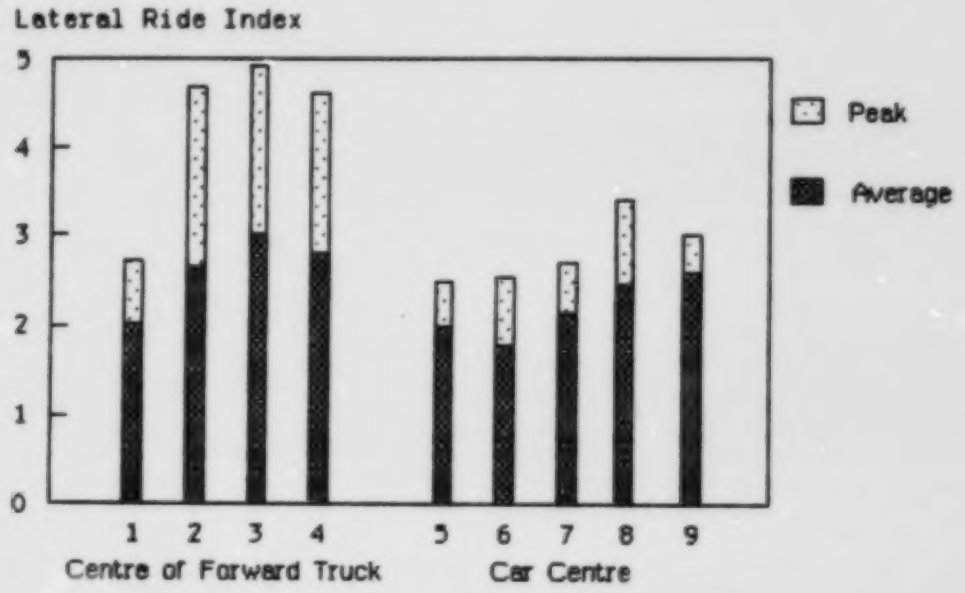


1 - GO Bi-Level
2 - GO Single-Level
3 - TEE Recent
4 - TEE Former
5 - GO Bi-Level Upper
6 - GO Bi-Level Lower
7 - GO Single-Level
8 - TEE Recent
9 - TEE Former

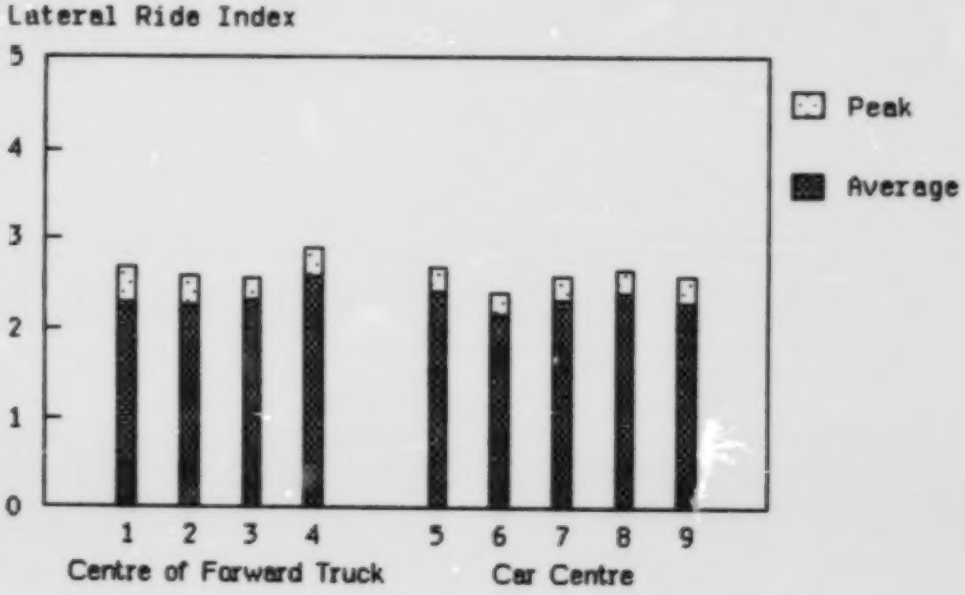
Figure 10/ British Rail Ride Meter Peak and Average Output

Test Track Section 3 Fair Tangent

(a) Lateral



(b) Vertical



1 - GO Bi-Level
2 - GO Single-Level
3 - TEE Recent
4 - TEE Former
5 - GO Bi-Level Upper
6 - GO Bi-Level Lower
7 - GO Single-Level
8 - TEE Recent
9 - TEE Former

Figure 11/ British Rail Ride Meter Peak and Average Output

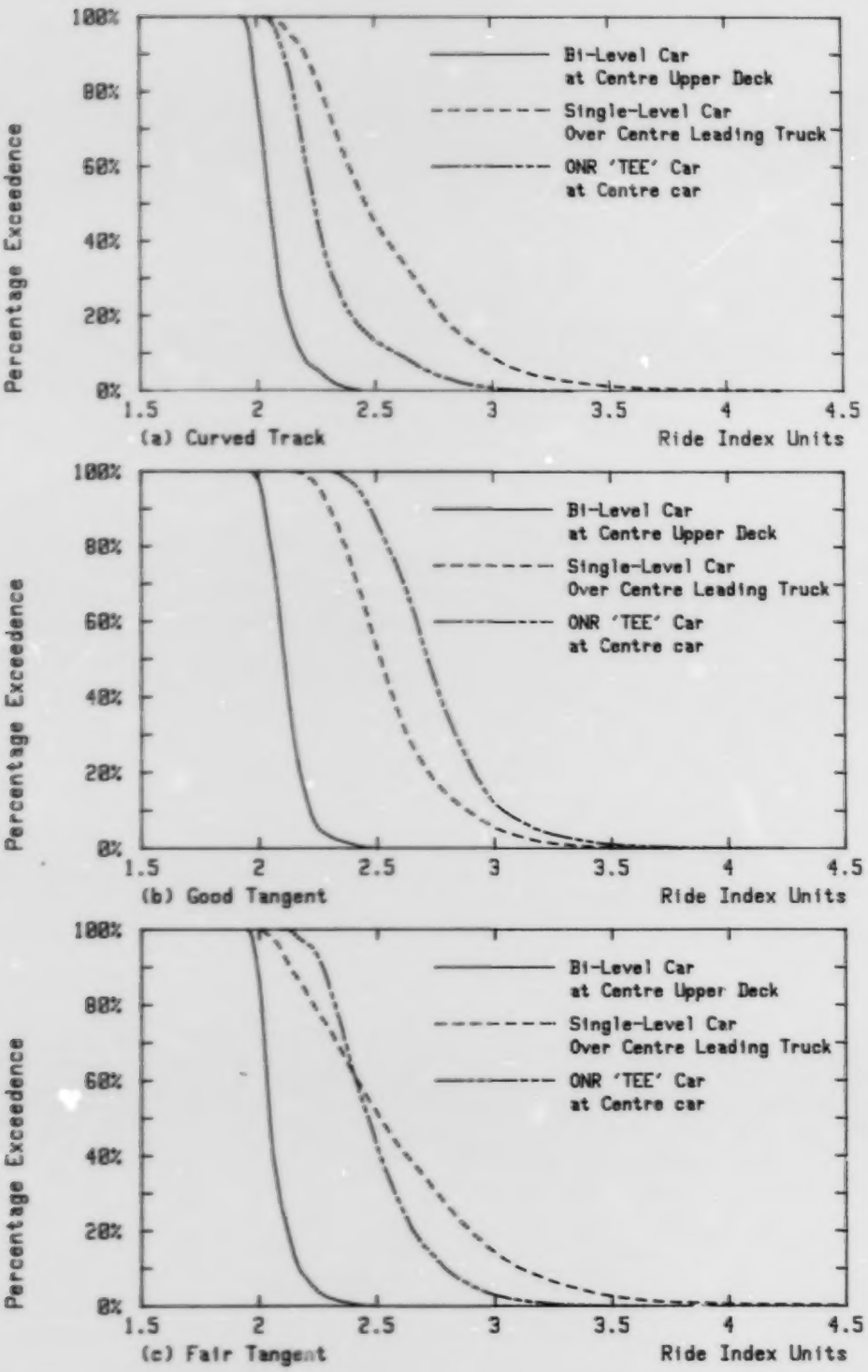


Figure 12/ Lateral British Rail Ride Index Percentage Exceedance Curves

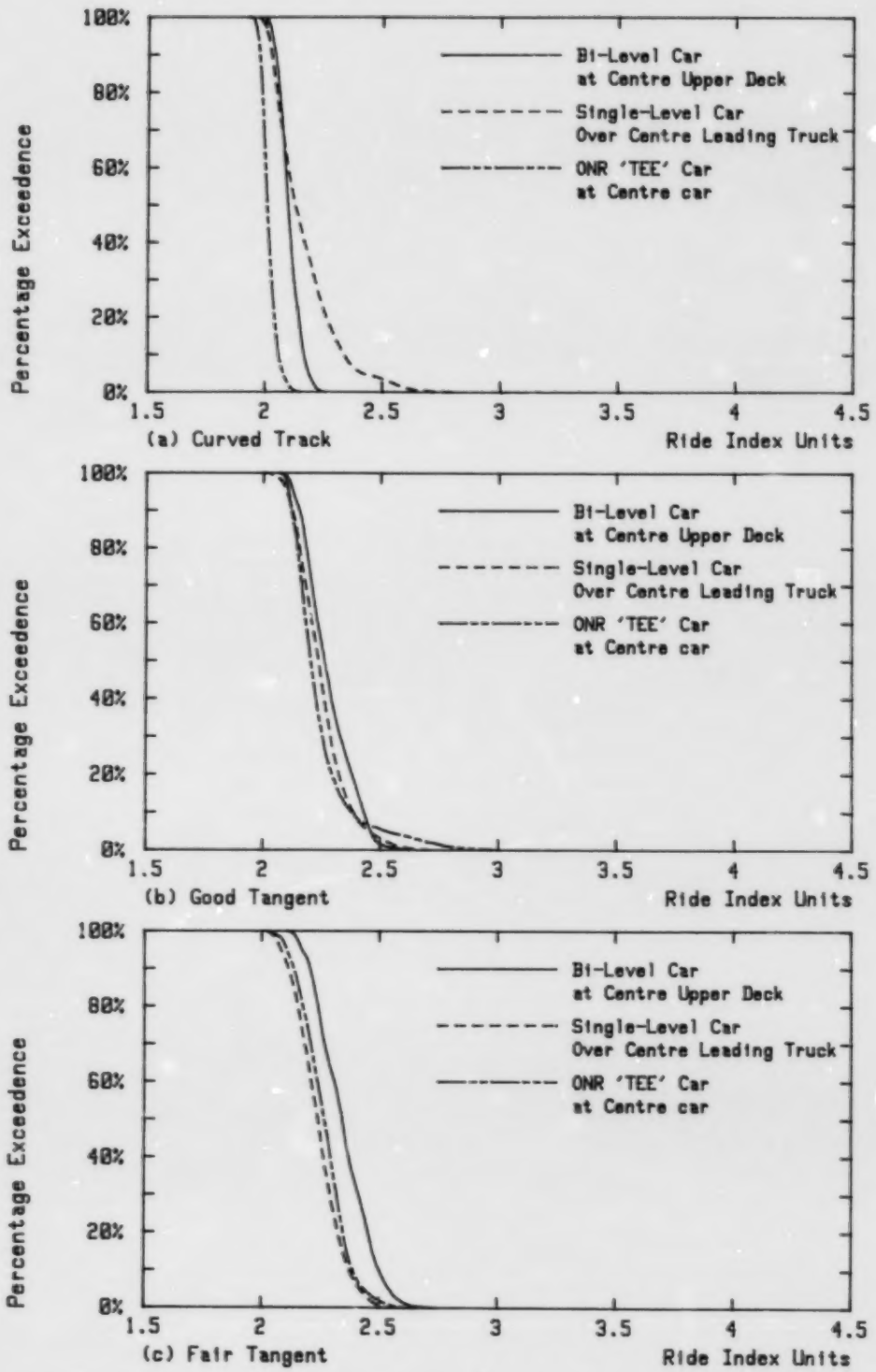


Figure 13/ Vertical British Rail Ride Index Percentage Exceedance Curves

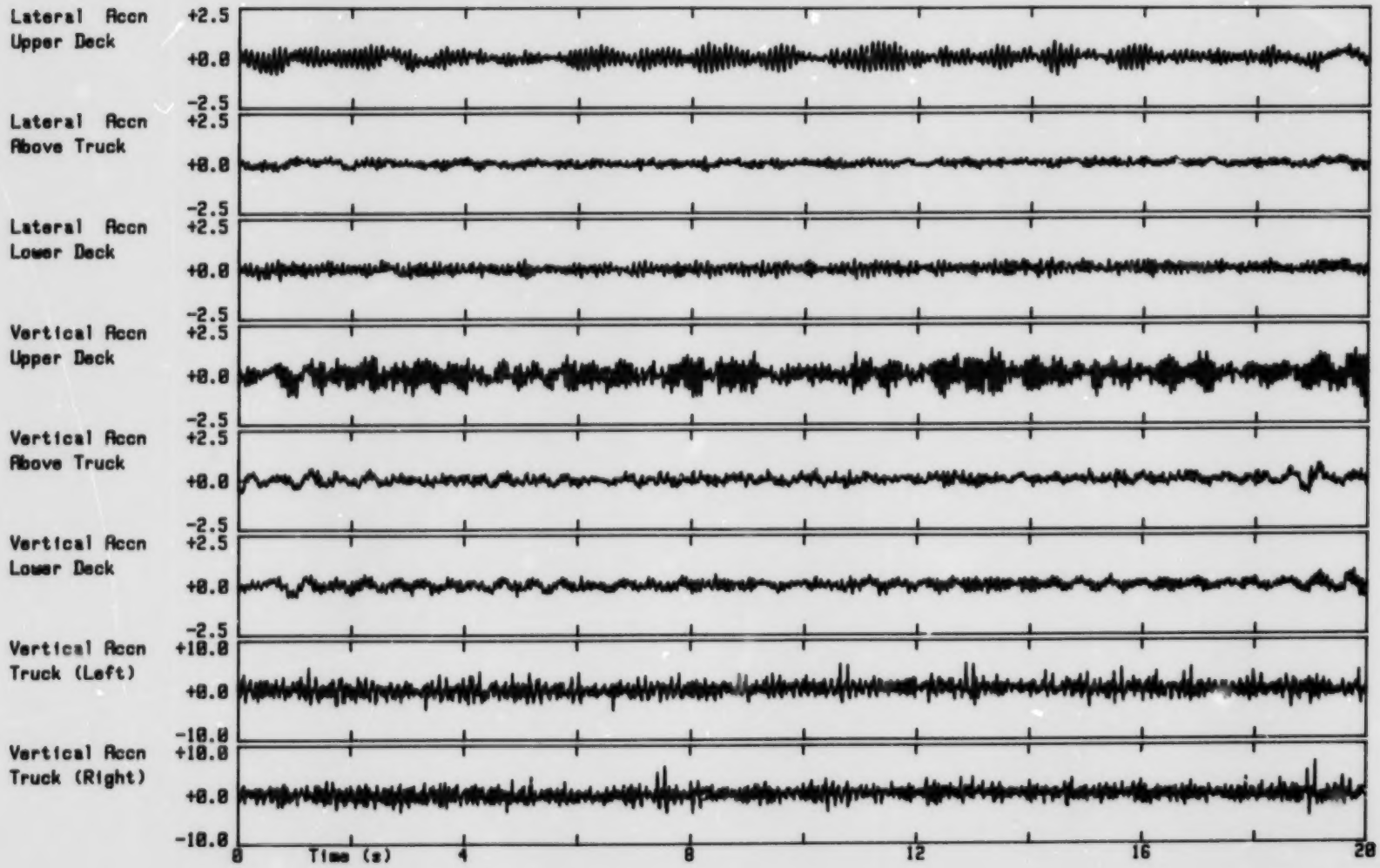


Figure 14/ Typical Acceleration Time Histories, Curved Track, Bi-Level Car, (Accn's in m/s^2)

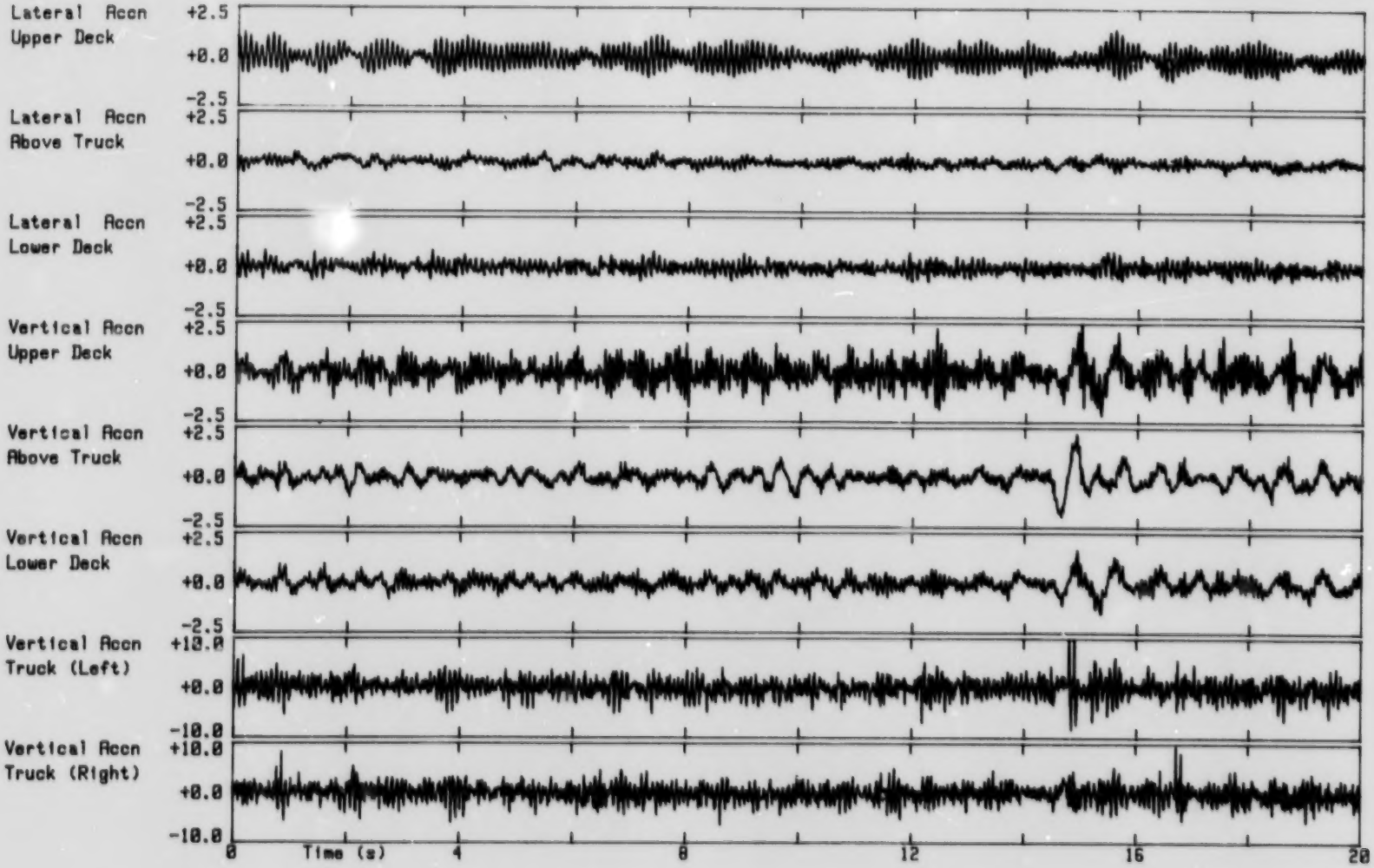


Figure 15/ Typical Acceleration Time Histories, Good Tangent, Bi-Level Car, (Accn's in m/s^2)

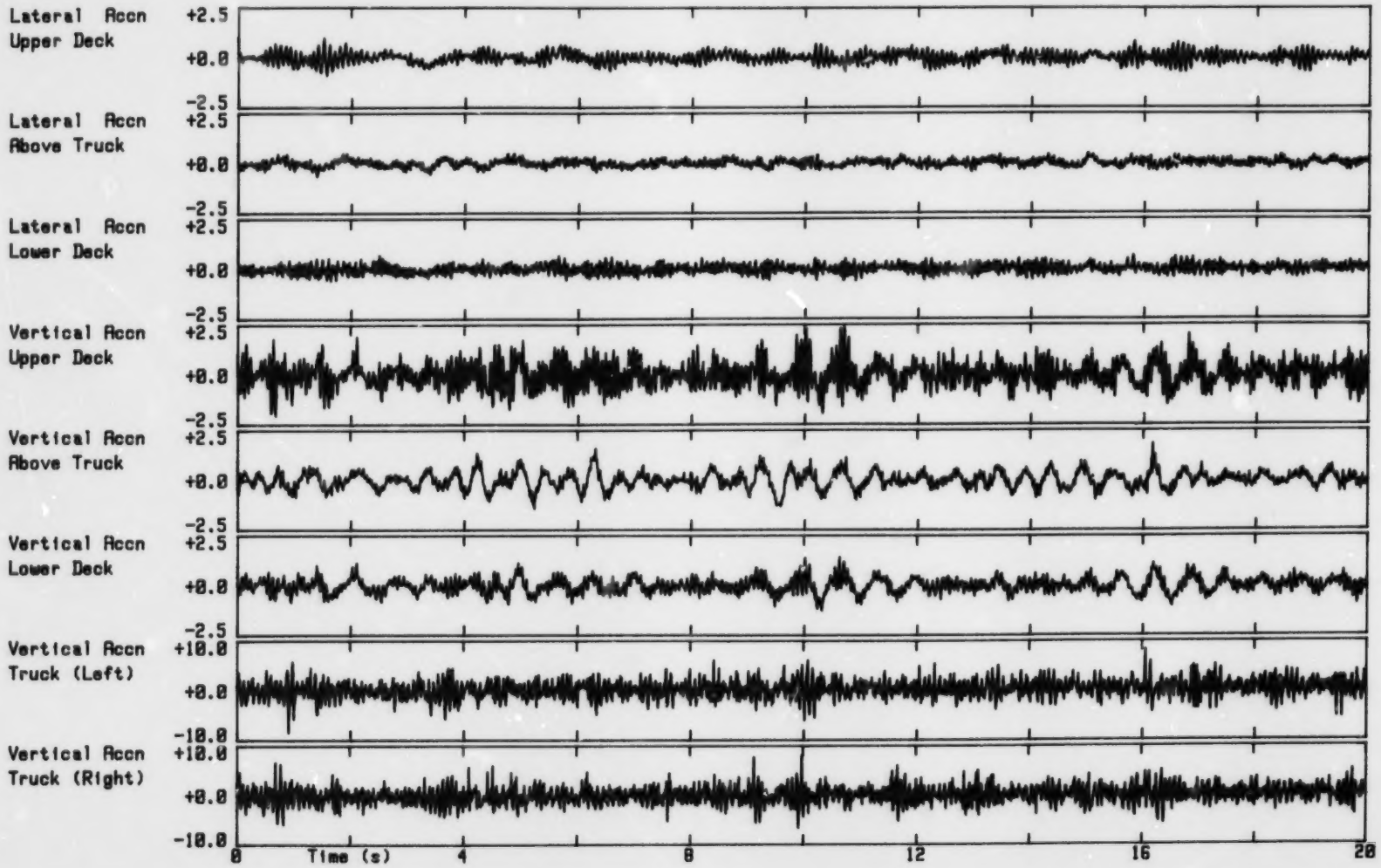


Figure 16/ Typical Acceleration Time Histories, Fair Tangent, Bi-Level Car, (Accn's in m/s^2)

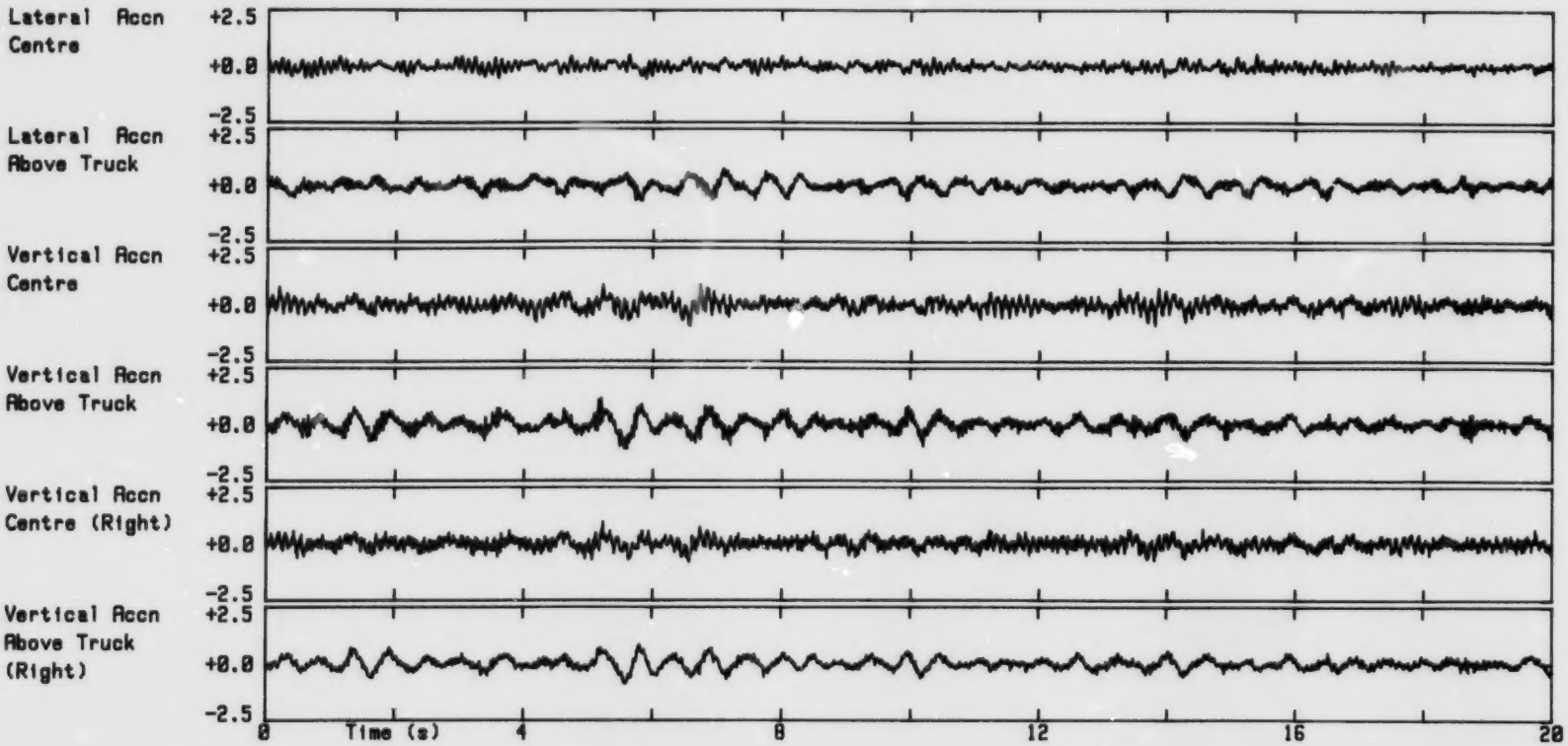


Figure 17/ Typical Acceleration Time Histories, Curved Track, Single-Level Car, (Accn's in m/s^2)

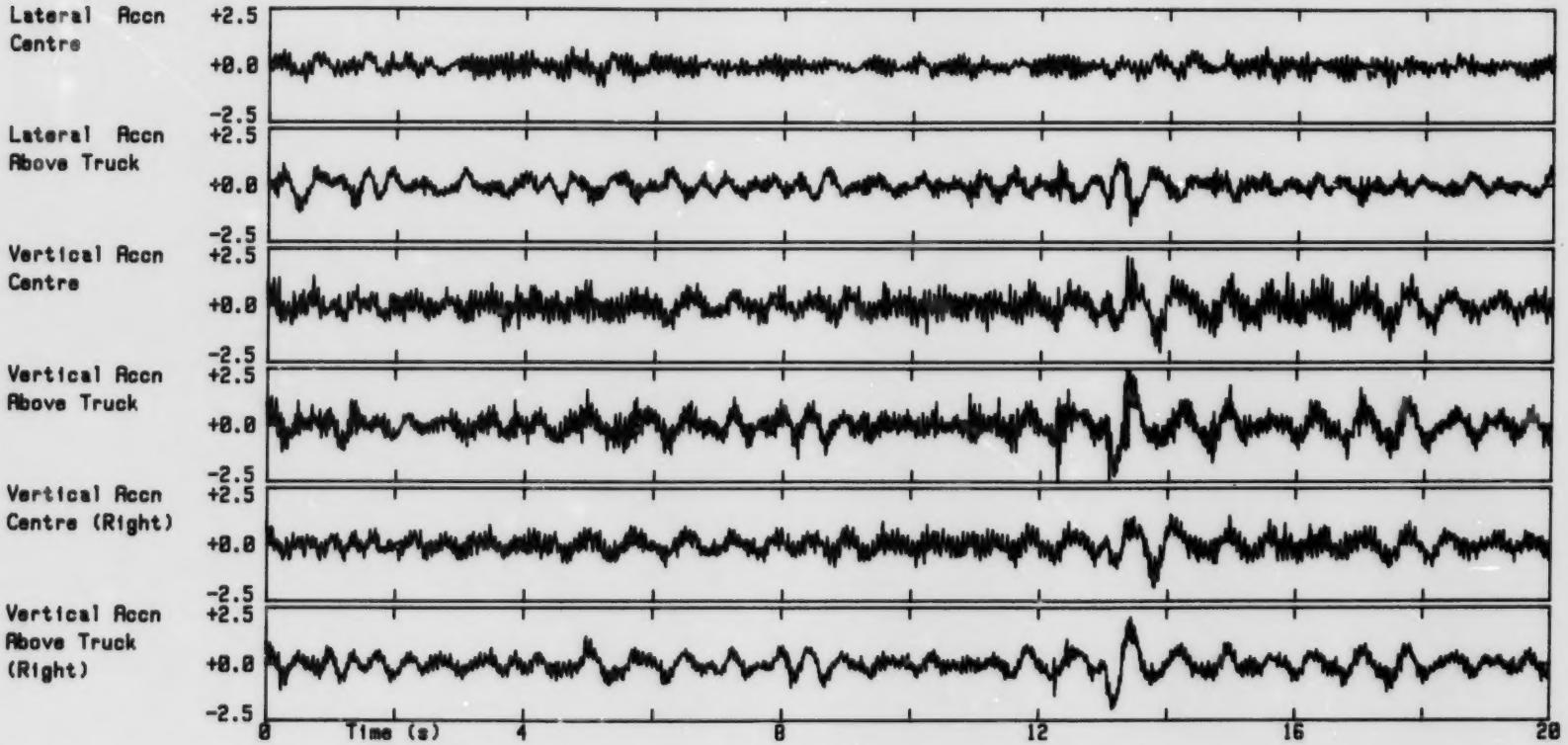


Figure 18/ Typical Acceleration Time Histories, Good Tangent, Single-Level Car, (Accn's in m/s^2)

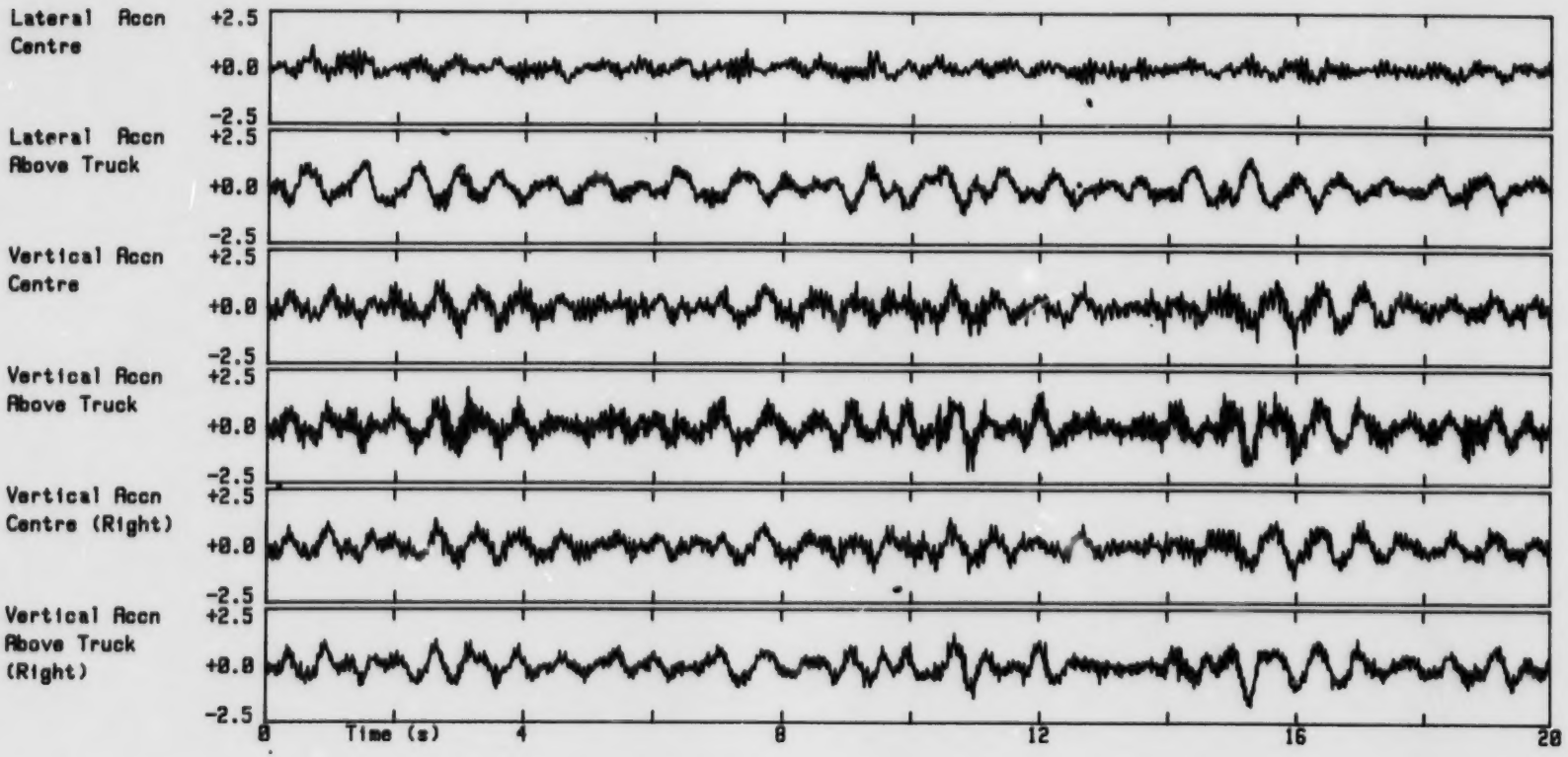


Figure 19/ Typical Acceleration Time Histories, Fair Tangent, Single-Level Car, (Accn's in m/s^2)

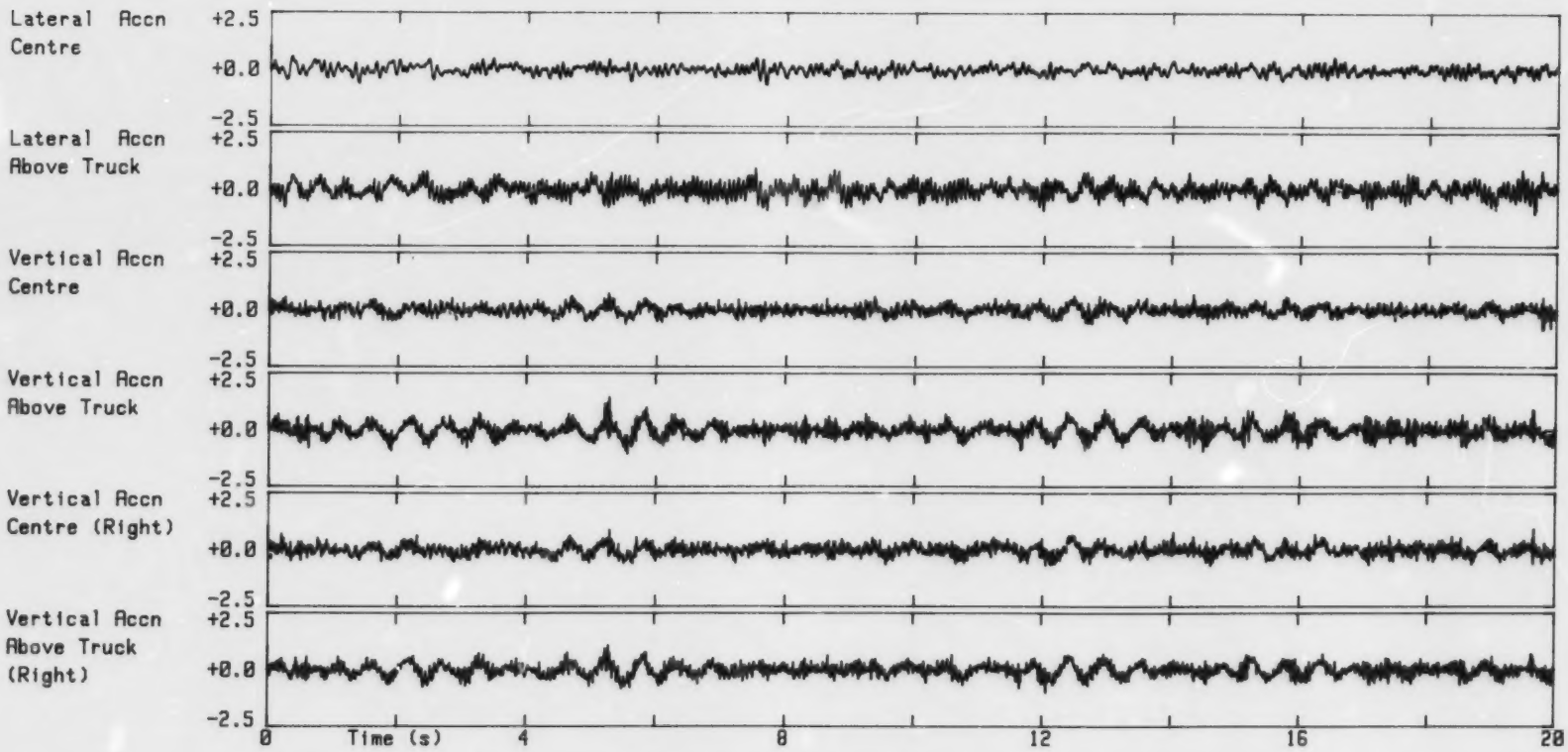


Figure 20/ Typical Acceleration Time Histories, Curved Track, ONR 'TEE' Car, (Accn's in m/s^2)

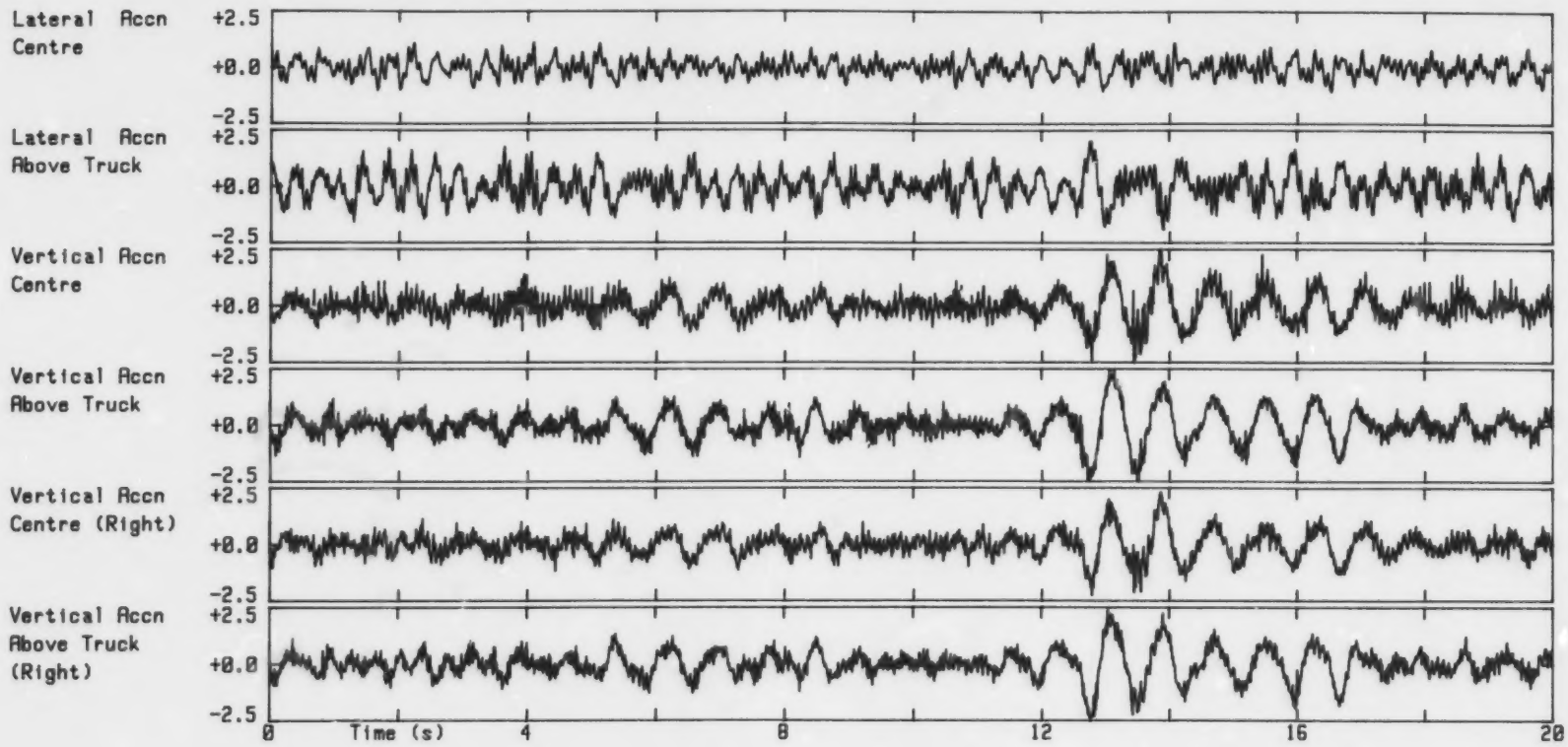


Figure 21/ Typical Acceleration Time Histories, Good Tangent, ONR 'TEE' Car, (Accn's in m/s^2)

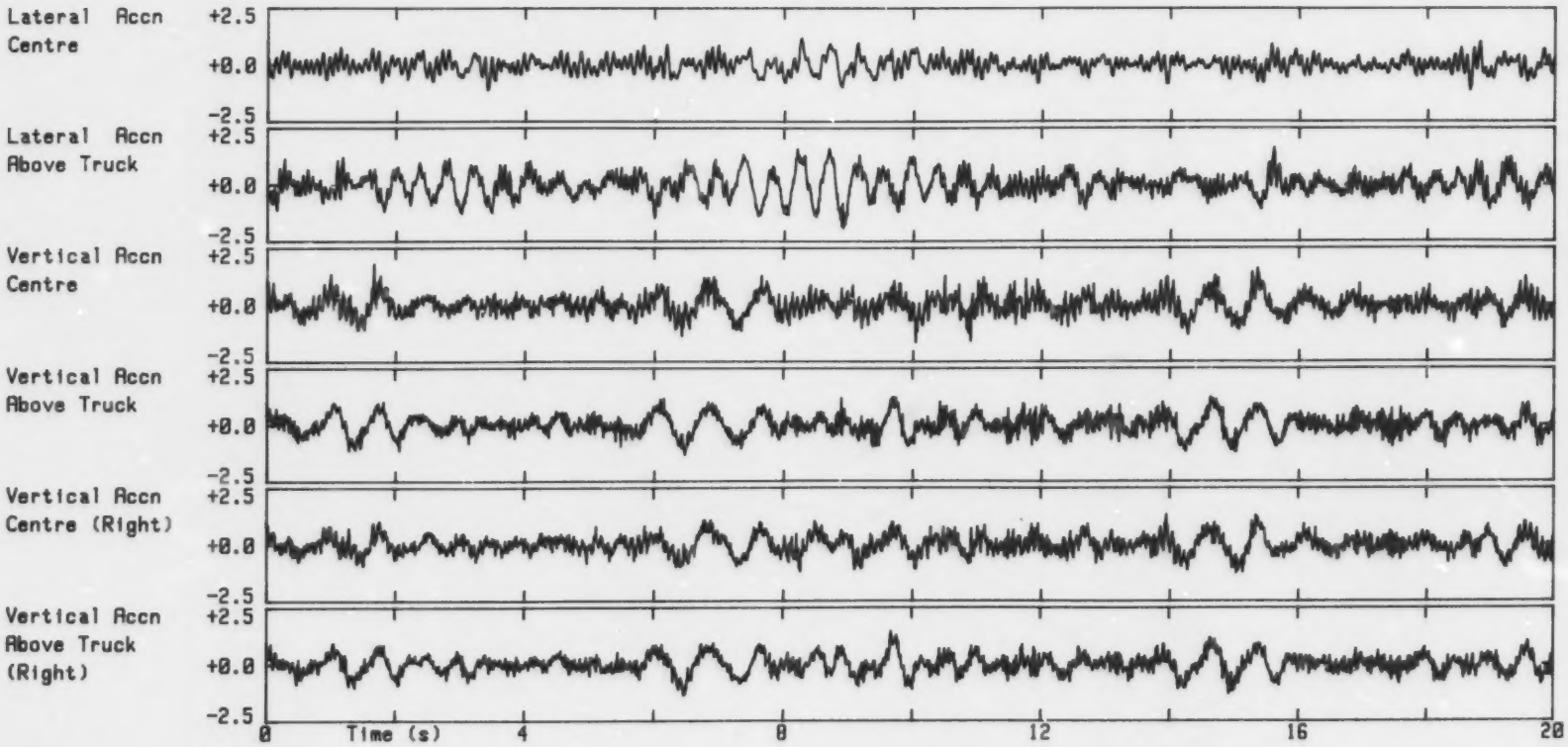


Figure 22/ Typical Acceleration Time Histories, Fair Tangent, ONR 'TEE' Car, (Accn's in m/s^2)

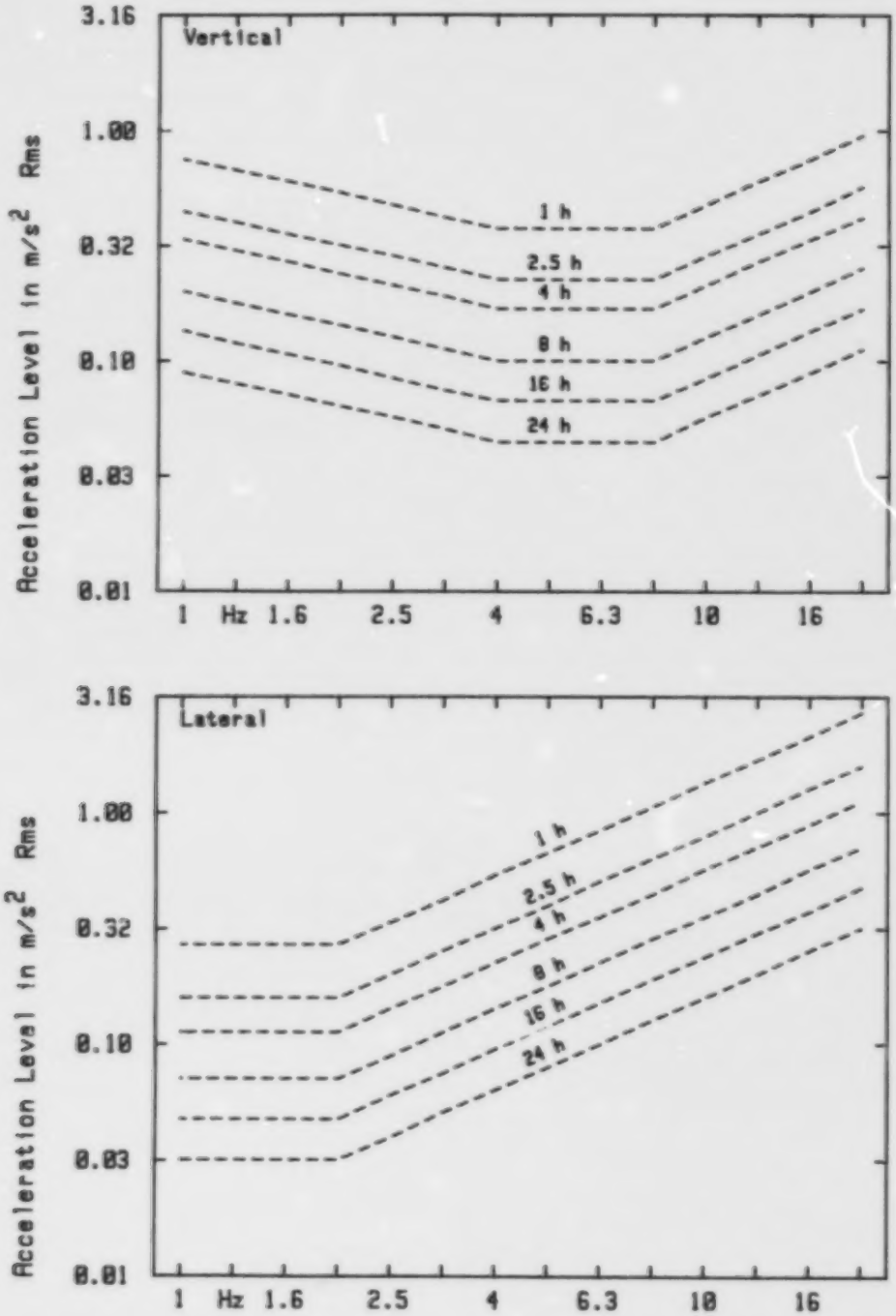


Figure 23/ ISO Reduced Comfort Boundaries

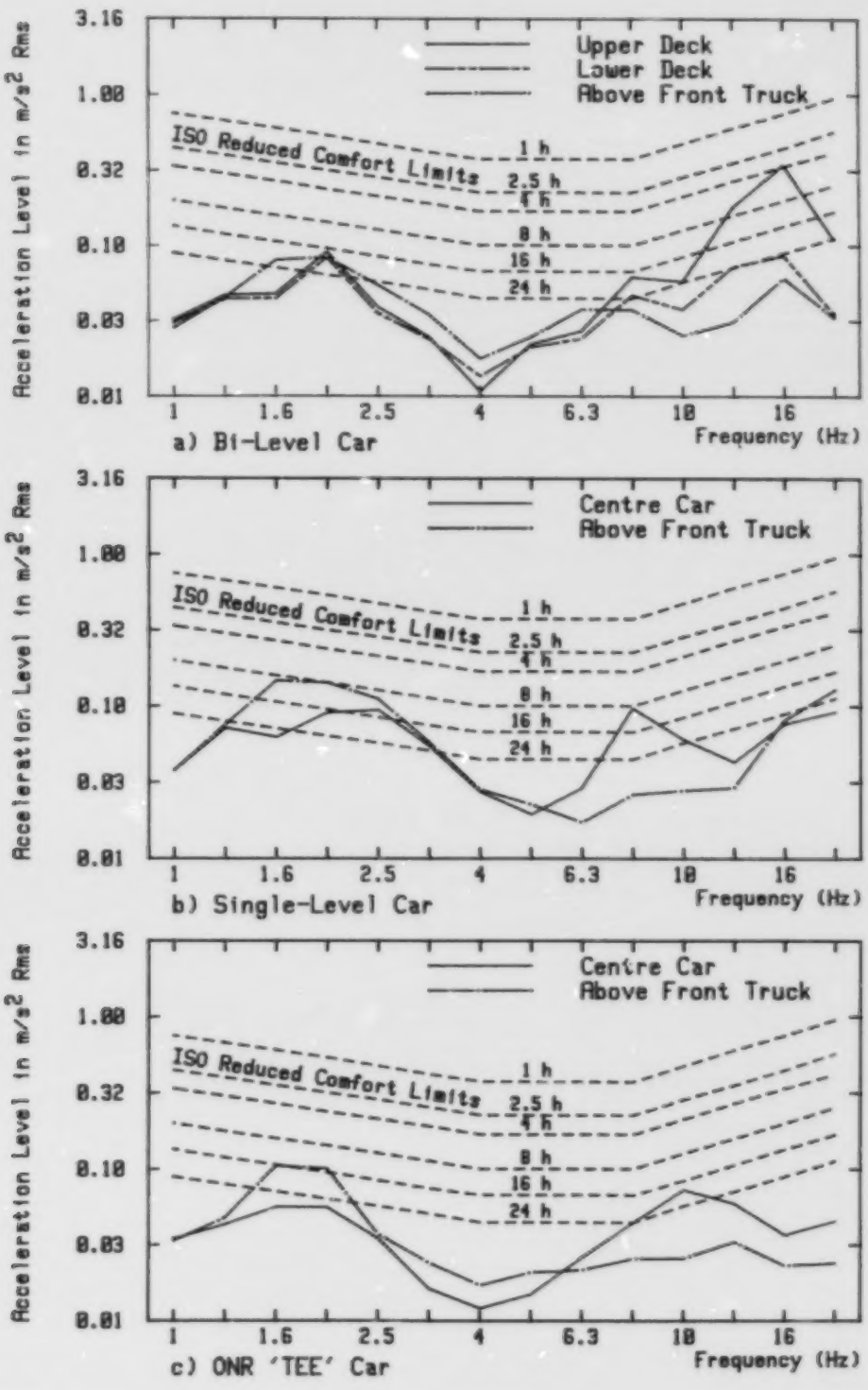


Figure 24/ Vertical Acceleration Spectra
Curved Track

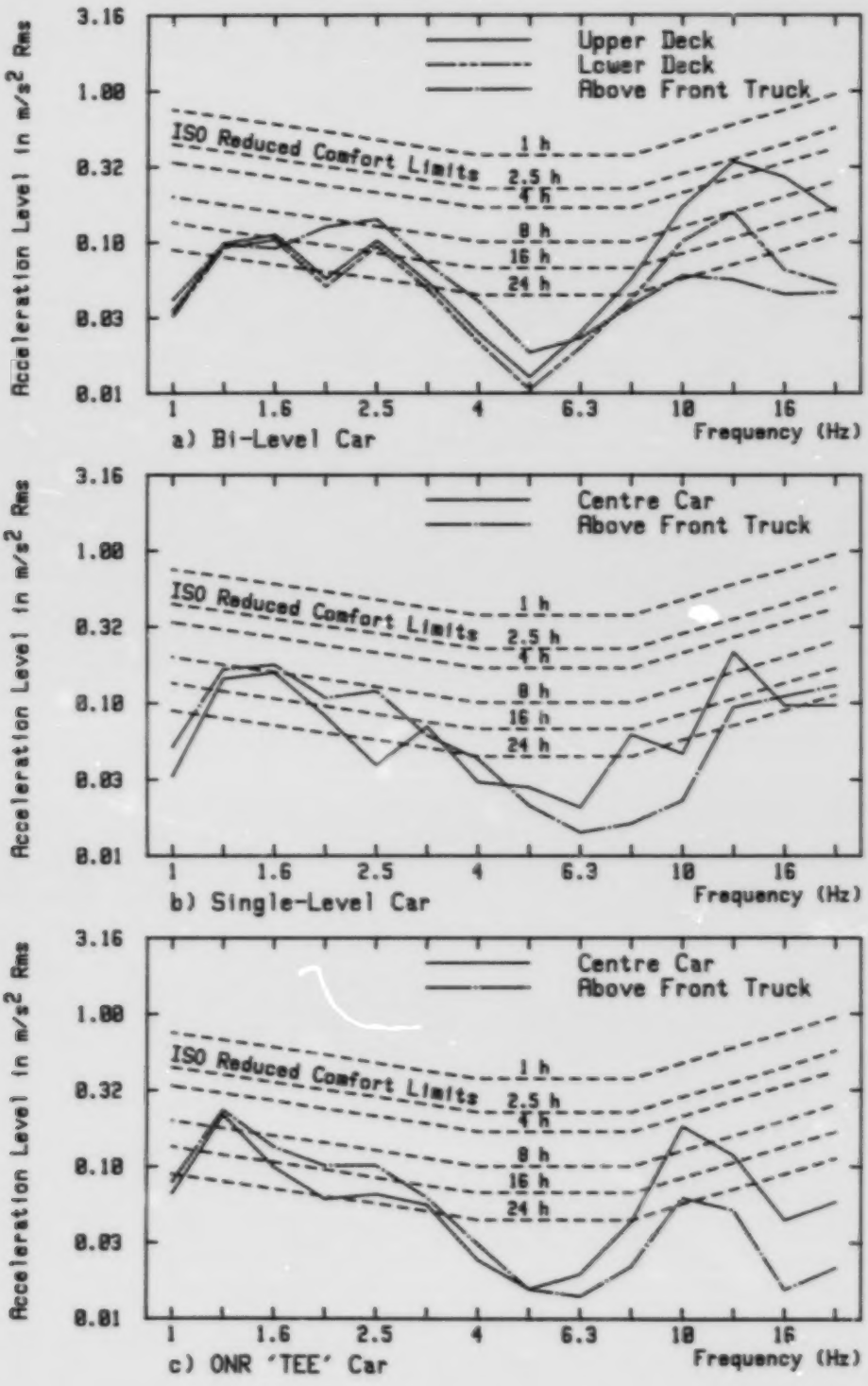


Figure 25/ Vertical Acceleration Spectra
Good Tangent

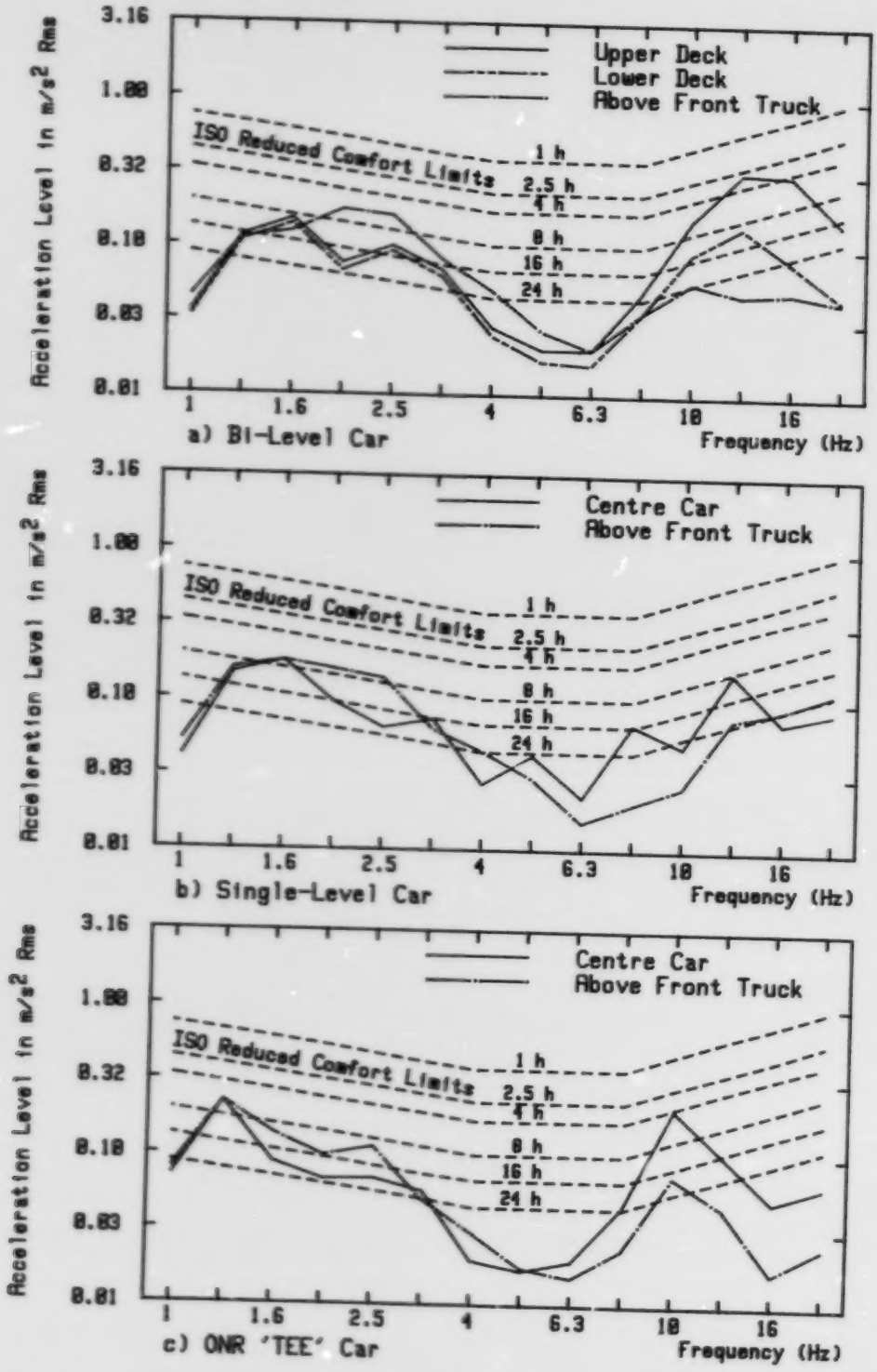


Figure 26/ Vertical Acceleration Spectra
Fair Tangent

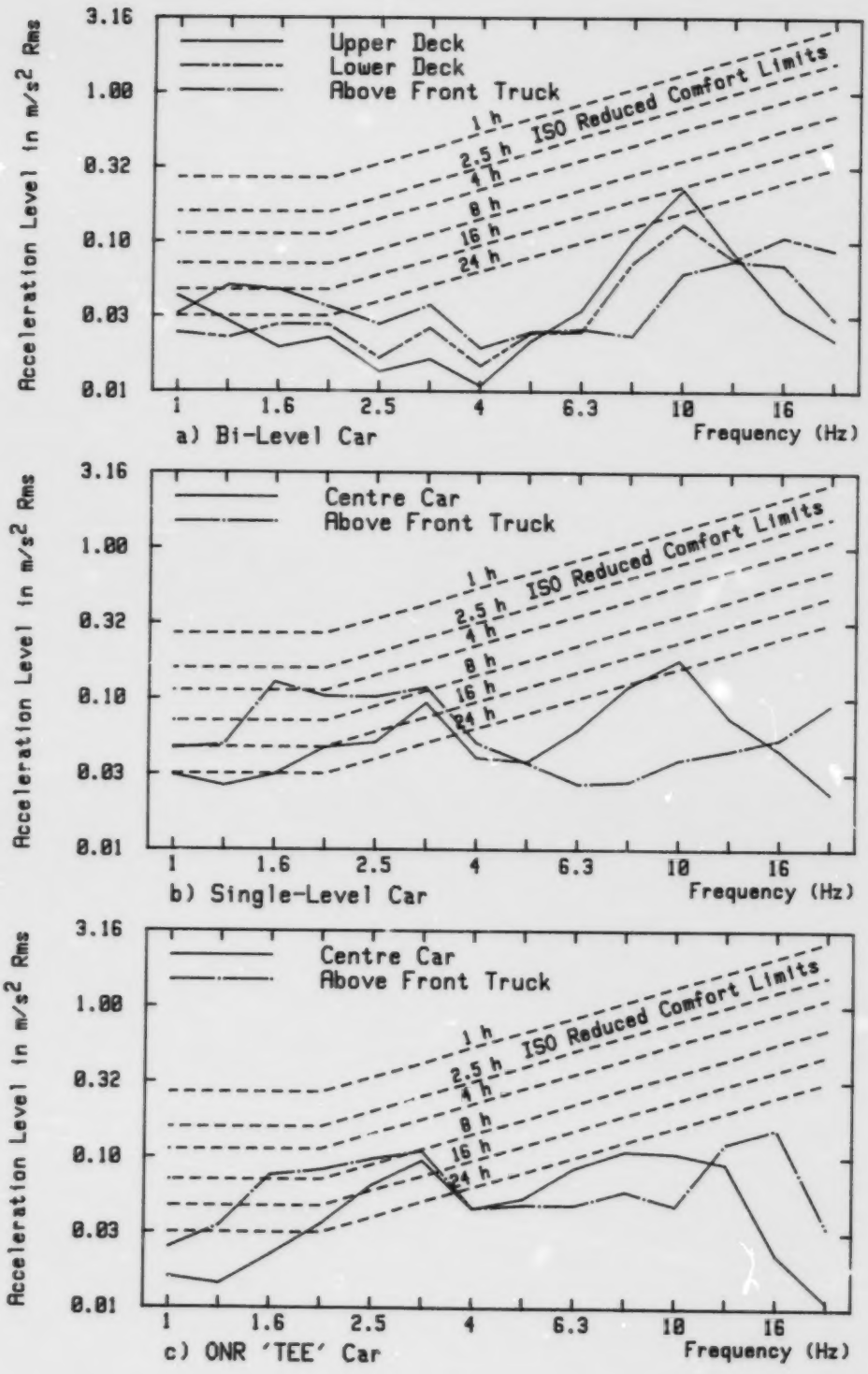


Figure 27/ Lateral Acceleration Spectra
Curved Track

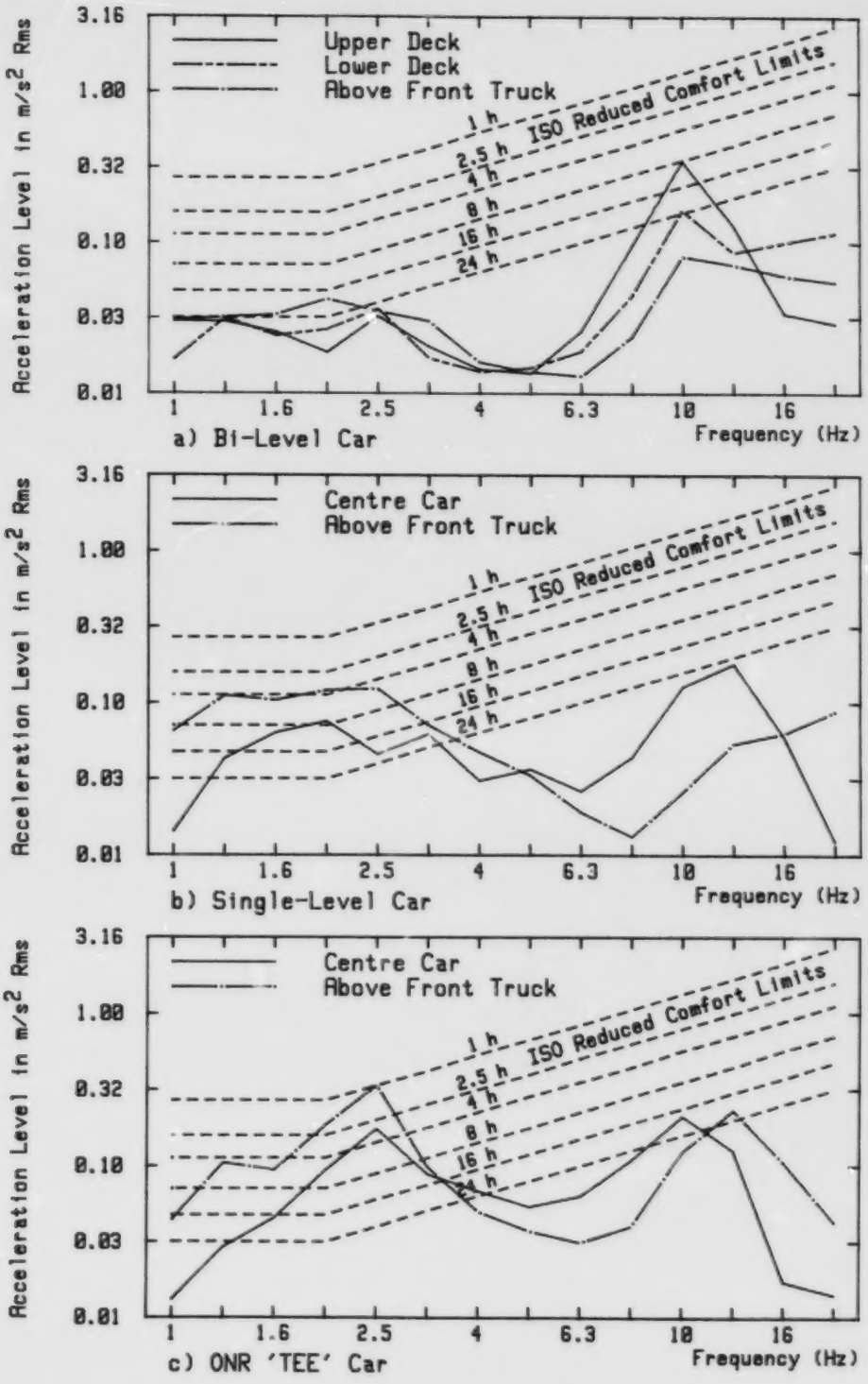


Figure 28/ Lateral Acceleration Spectra
Good Tangent

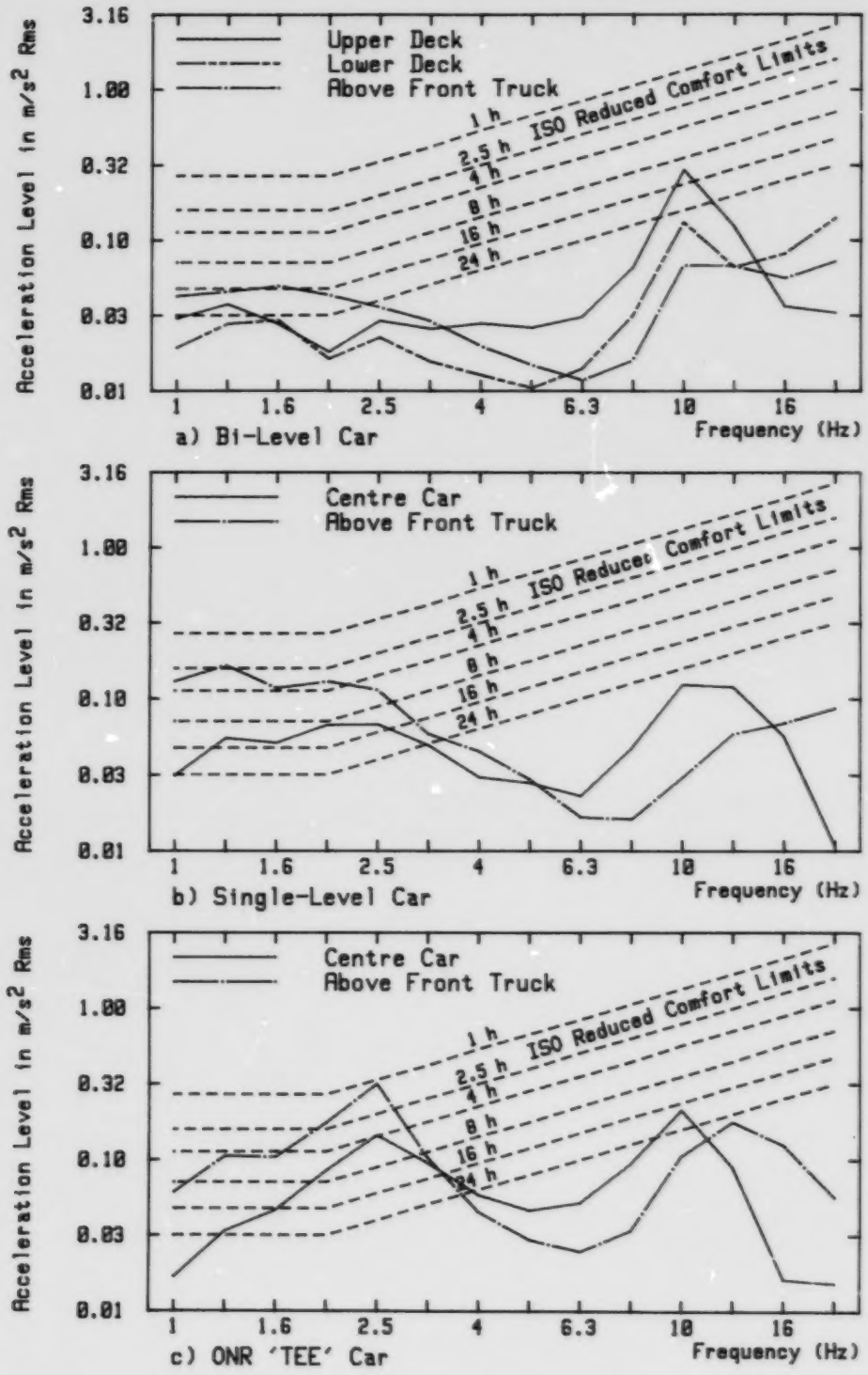


Figure 29/ Lateral Acceleration Spectra
Fair Tangent

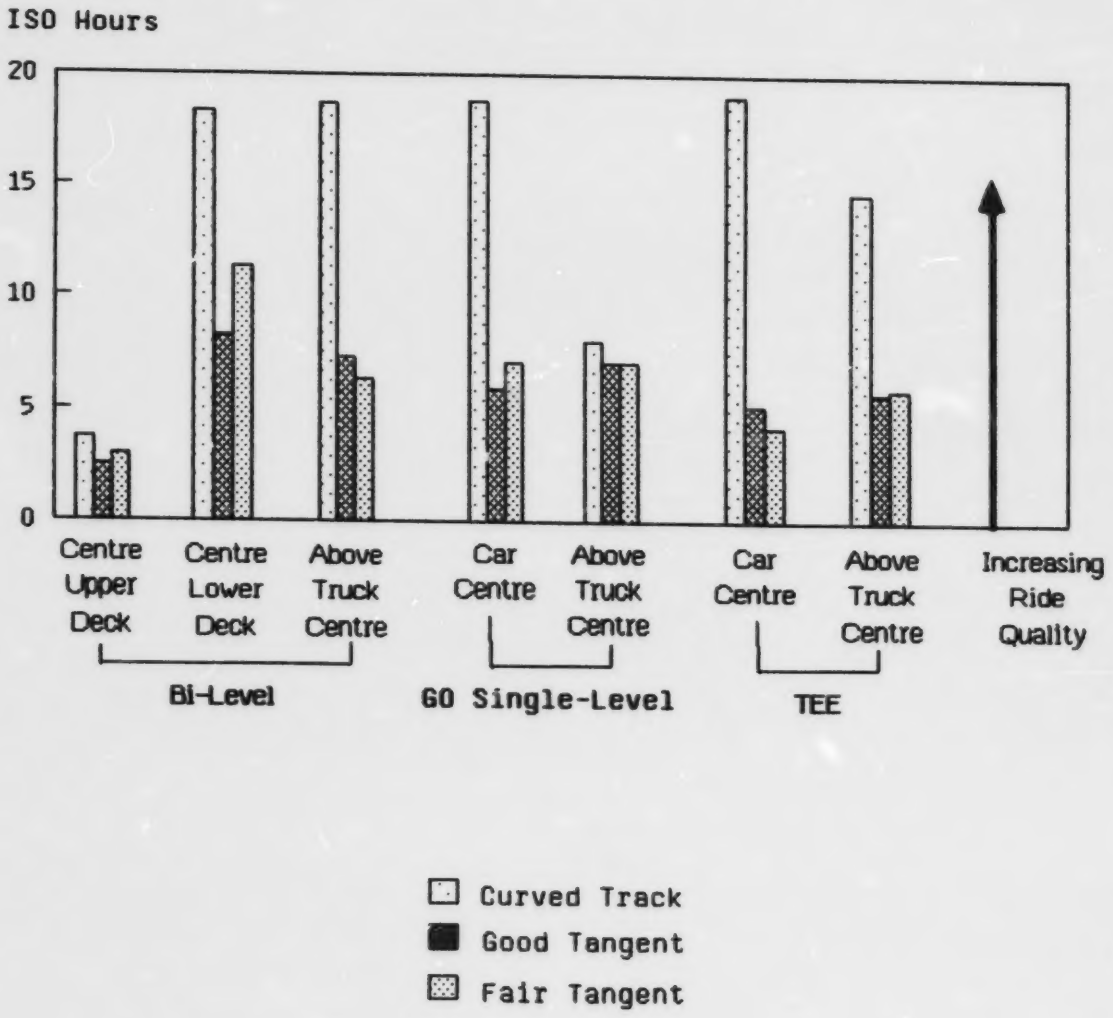


Figure 30/ Vertical Ride Quality

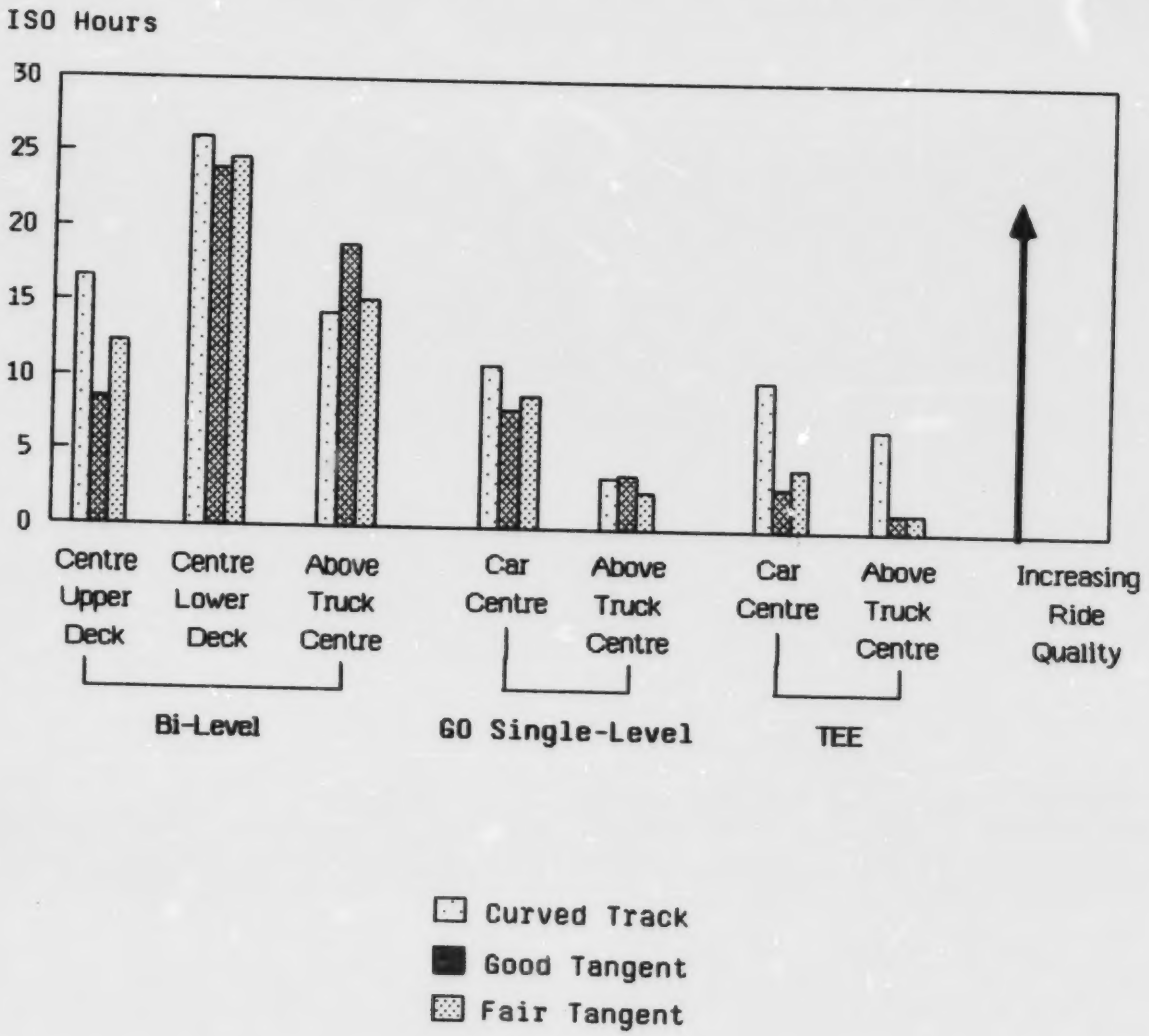


Figure 31/ Lateral Ride Quality

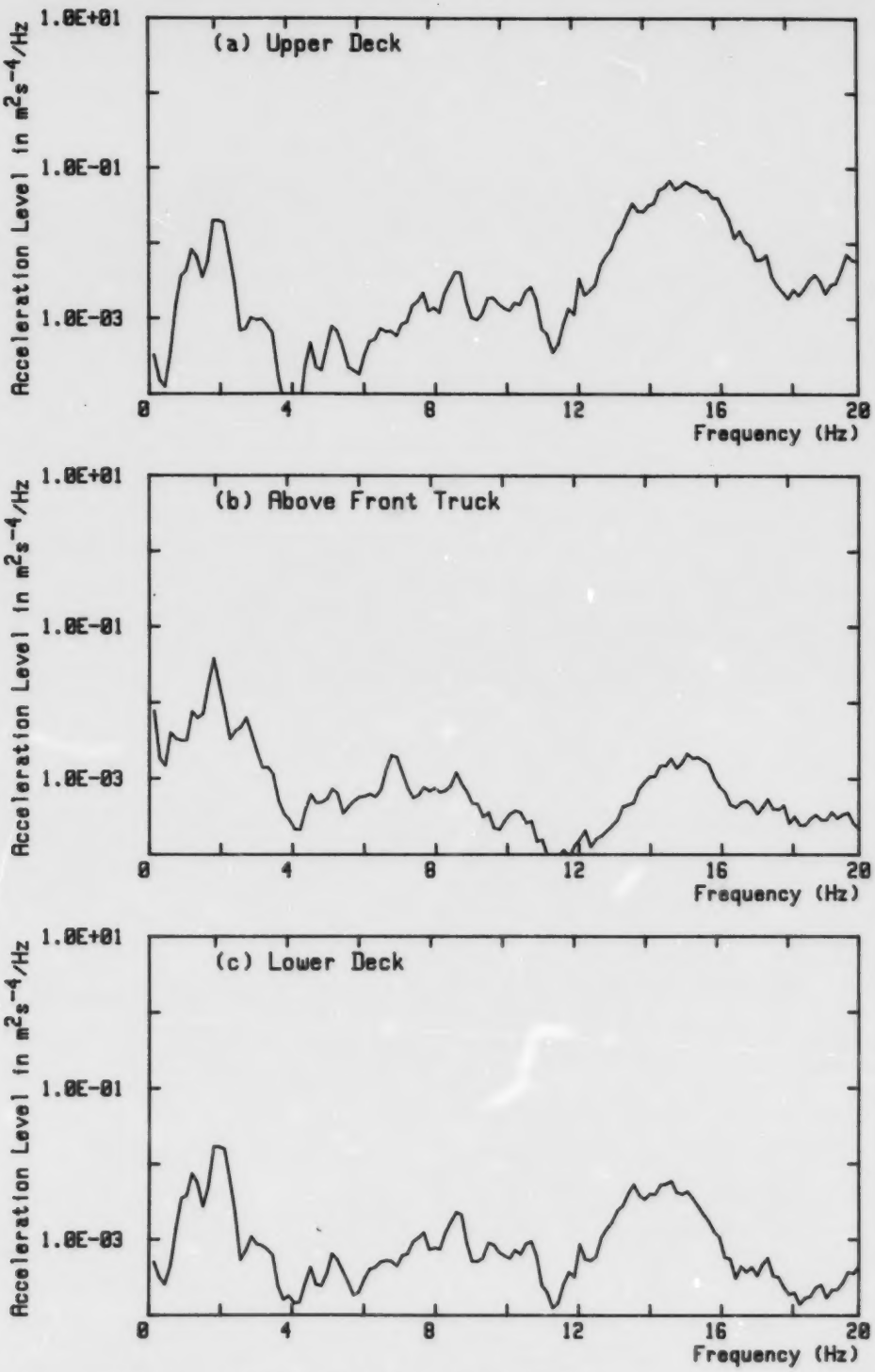


Figure 32/ Vertical Acceleration Spectra
Bi-Level Car Curved Track

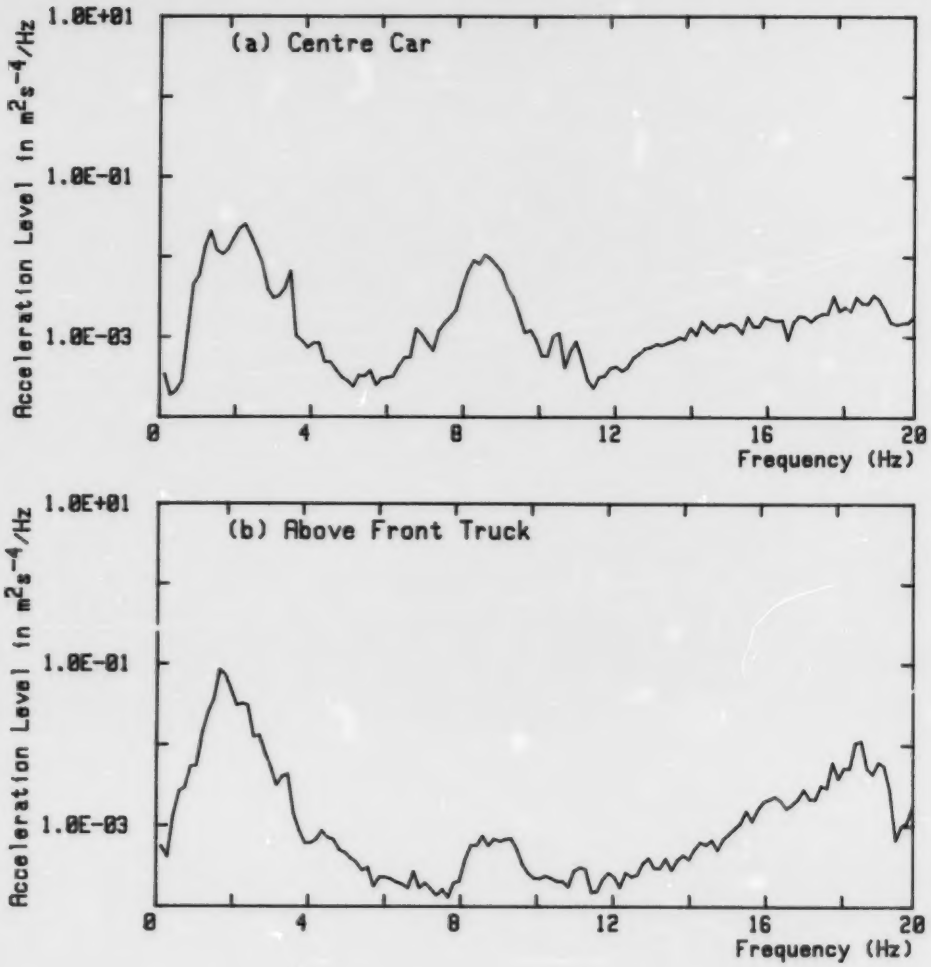


Figure 33/ Vertical Acceleration Spectra
Single-Level Car Curved Track

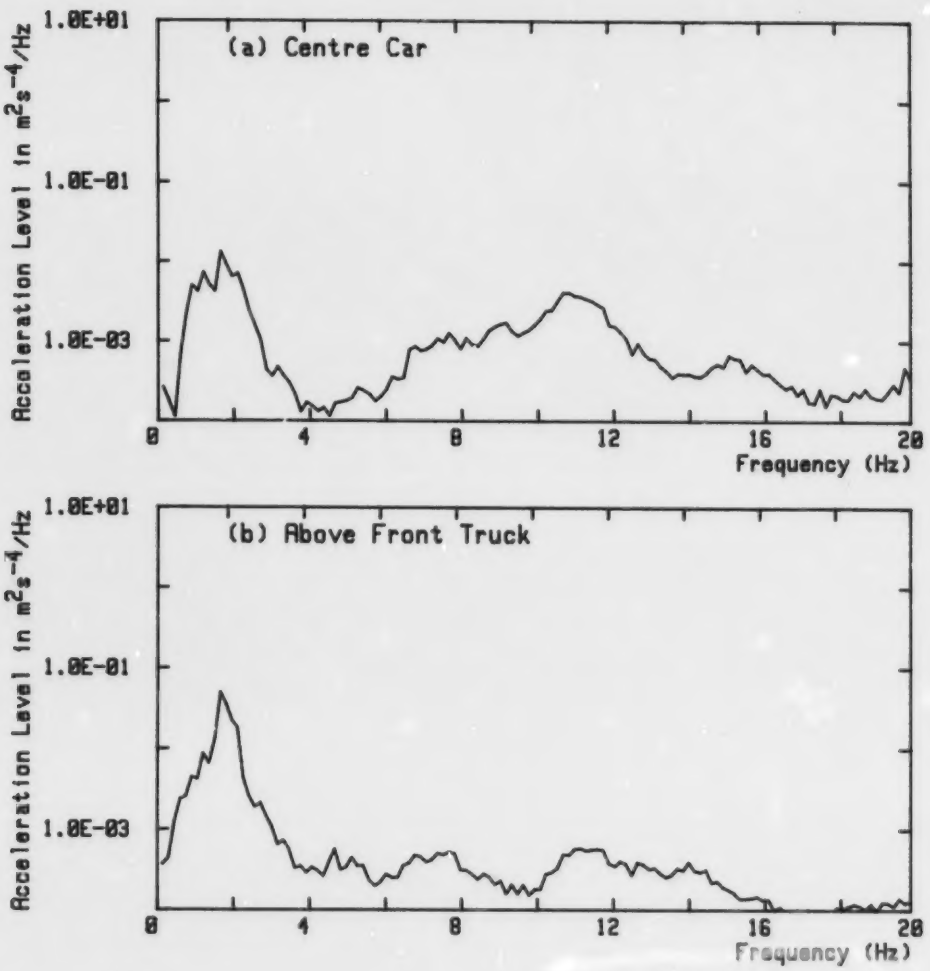


Figure 34/ Vertical Acceleration Spectra
ONR 'TEE' Car Curved Track

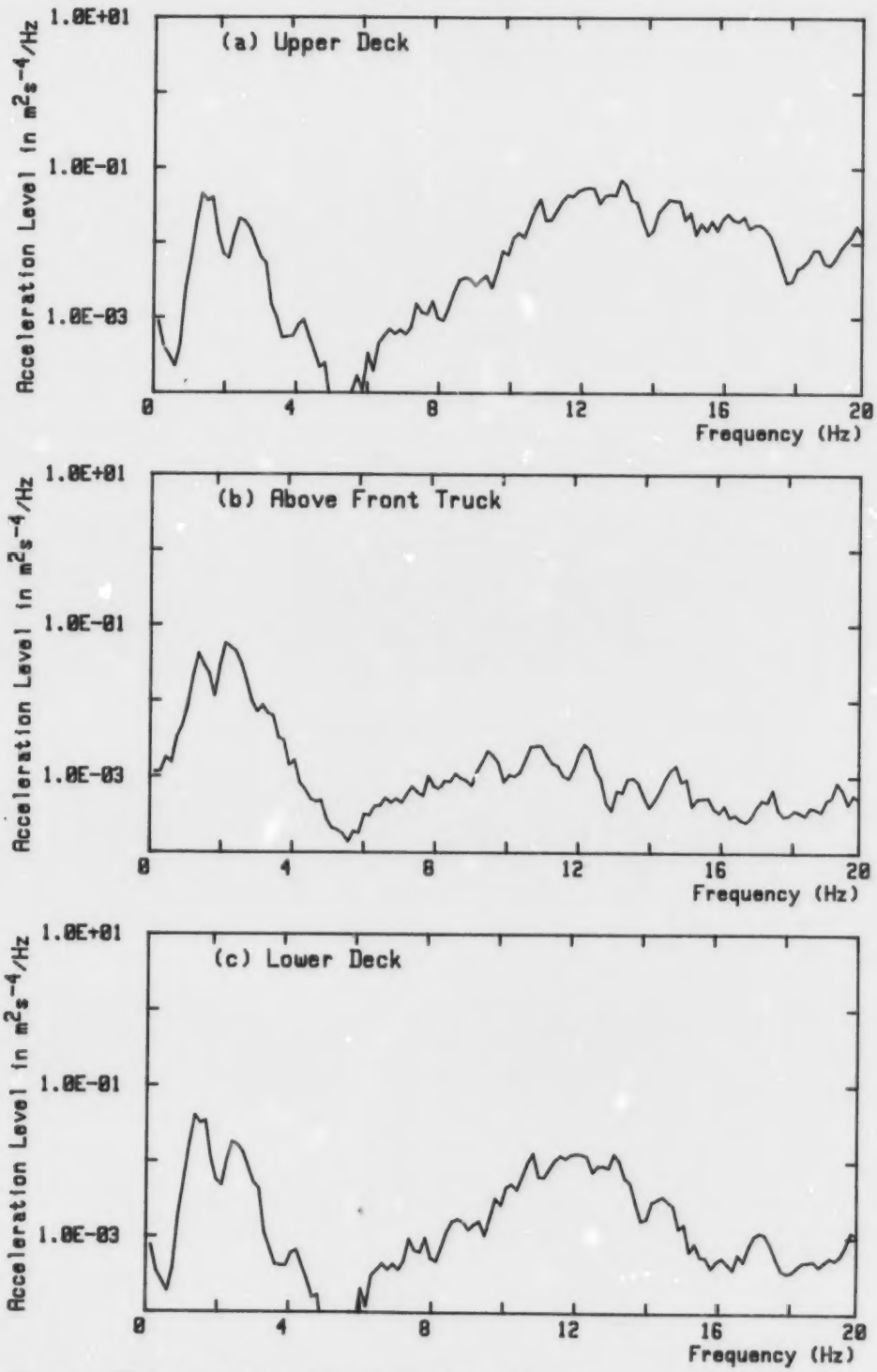


Figure 35/ Vertical Acceleration Spectra
Bi-Level Car Good Tangent

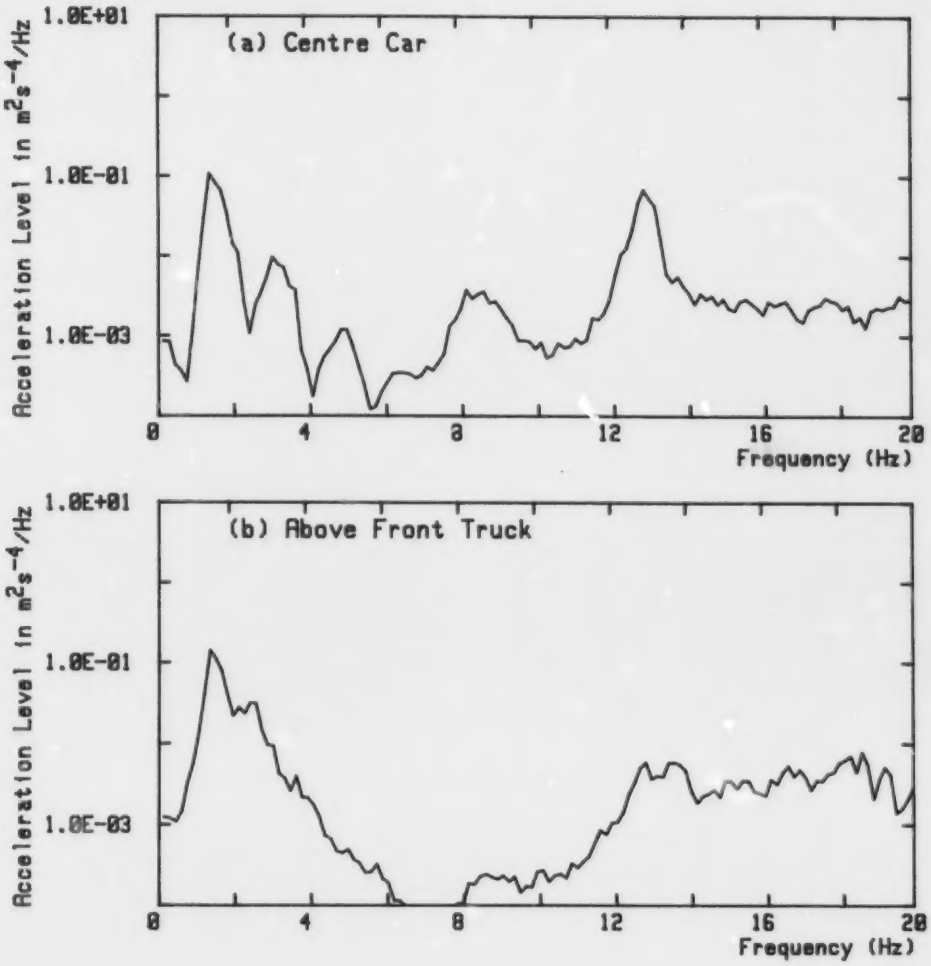


Figure 36/ Vertical Acceleration Spectra
Single-Level Car Good Tangent

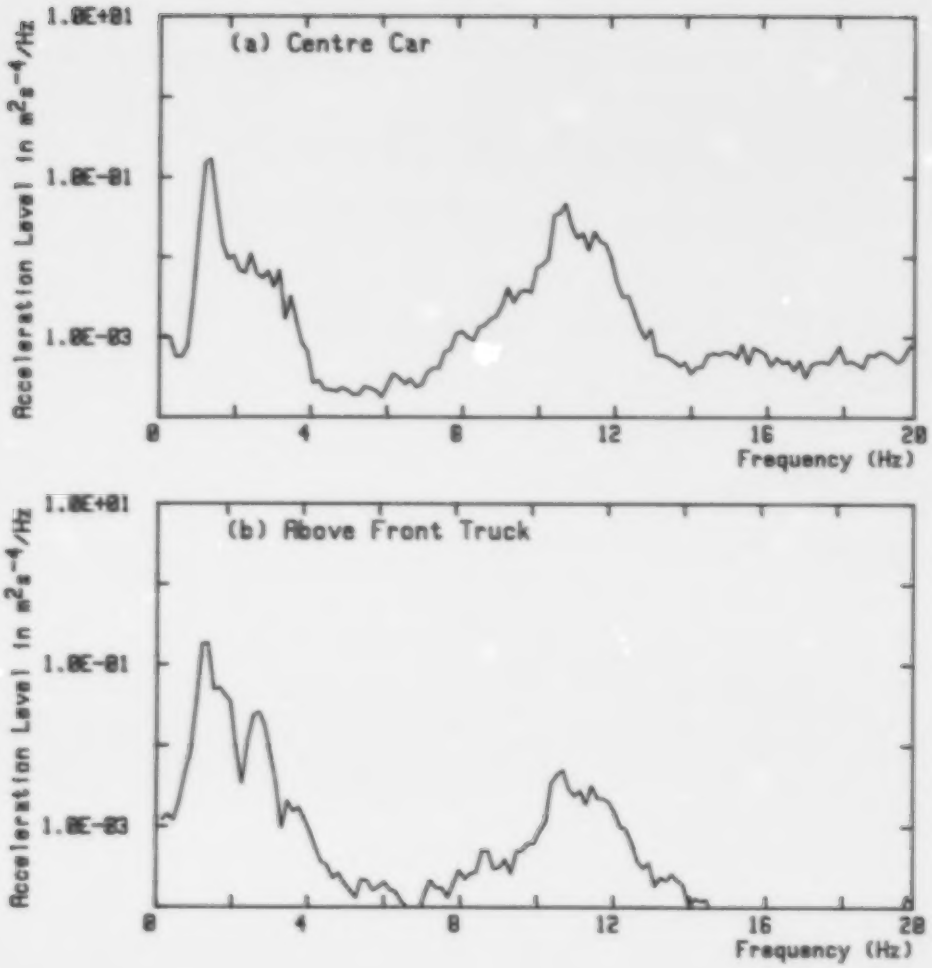


Figure 37/ Vertical Acceleration Spectra
ONR 'TEE' Car Good Tangent

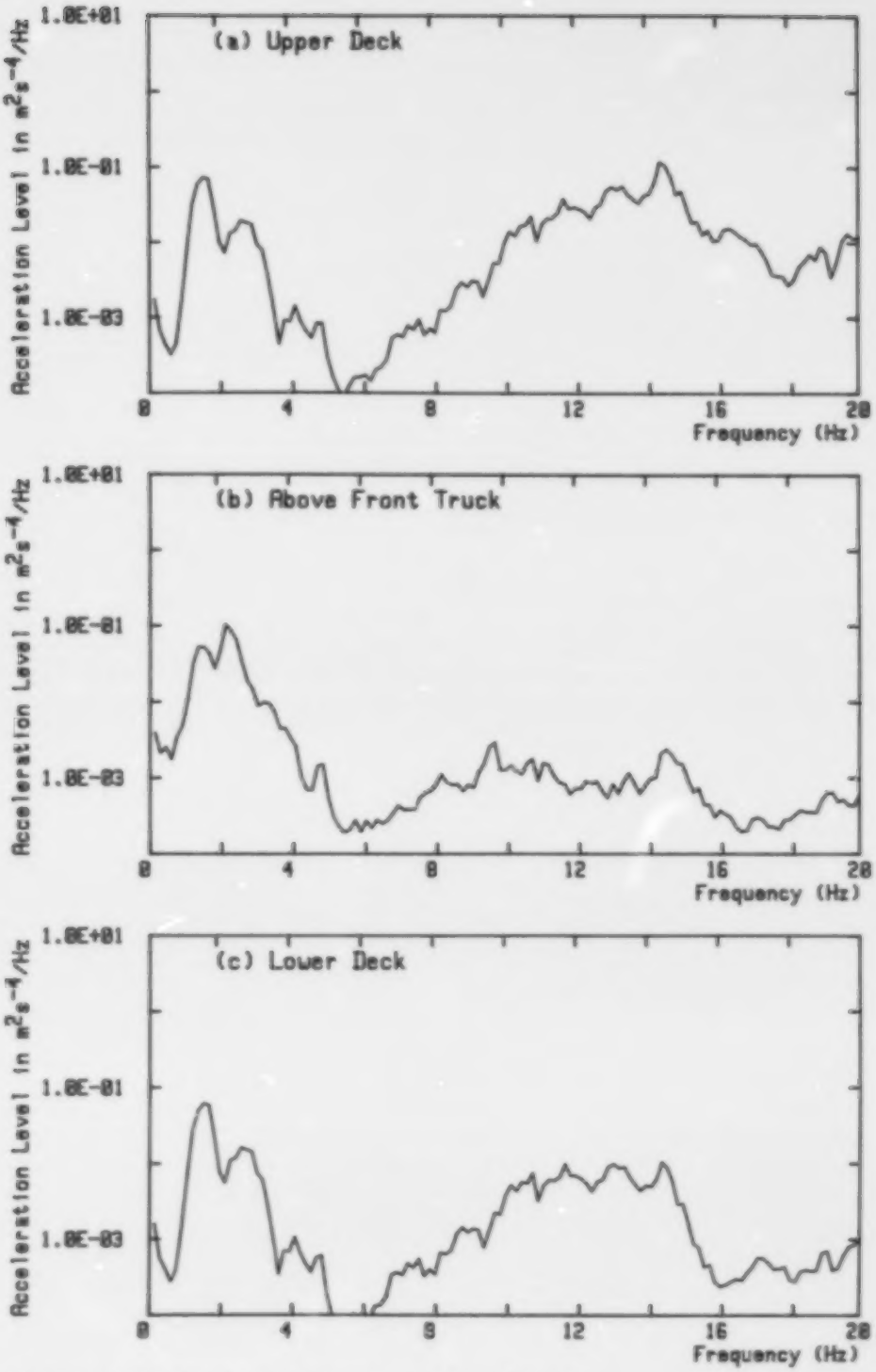


Figure 38/ Vertical Acceleration Spectra
Bi-Level Car Fair Tangent

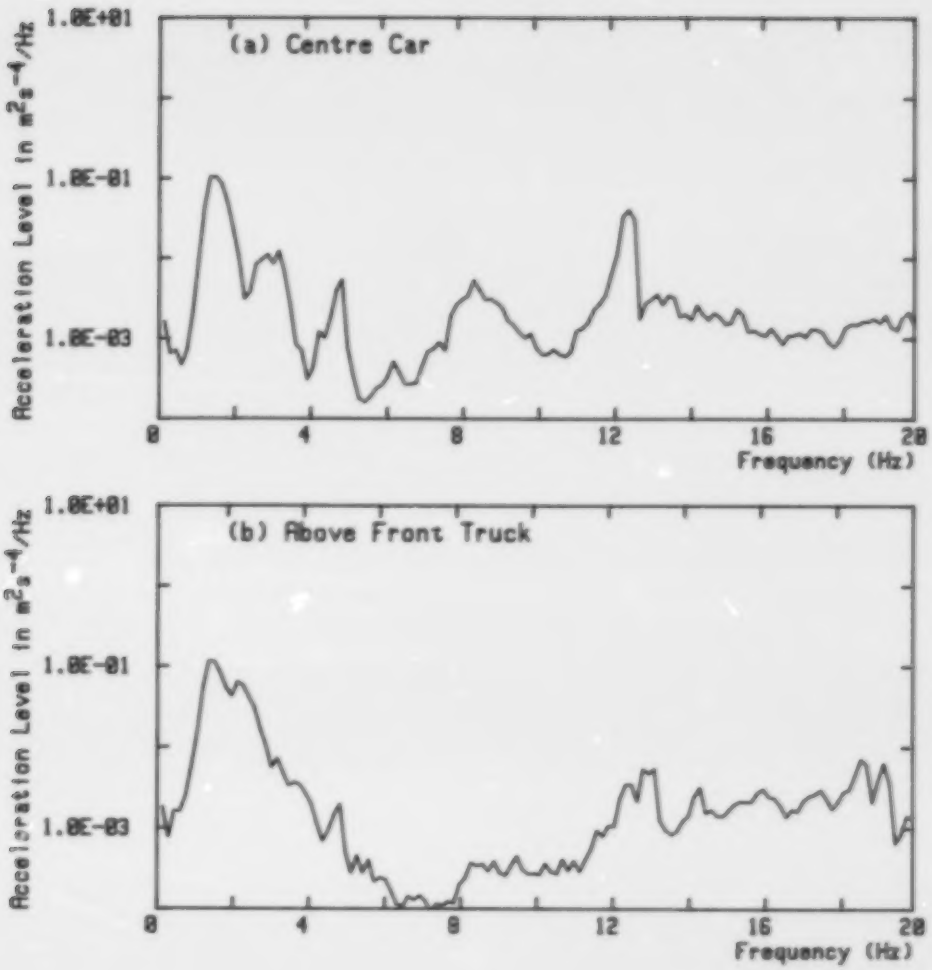


Figure 39/ Vertical Acceleration Spectra
Single-Level Car Fair Tangent

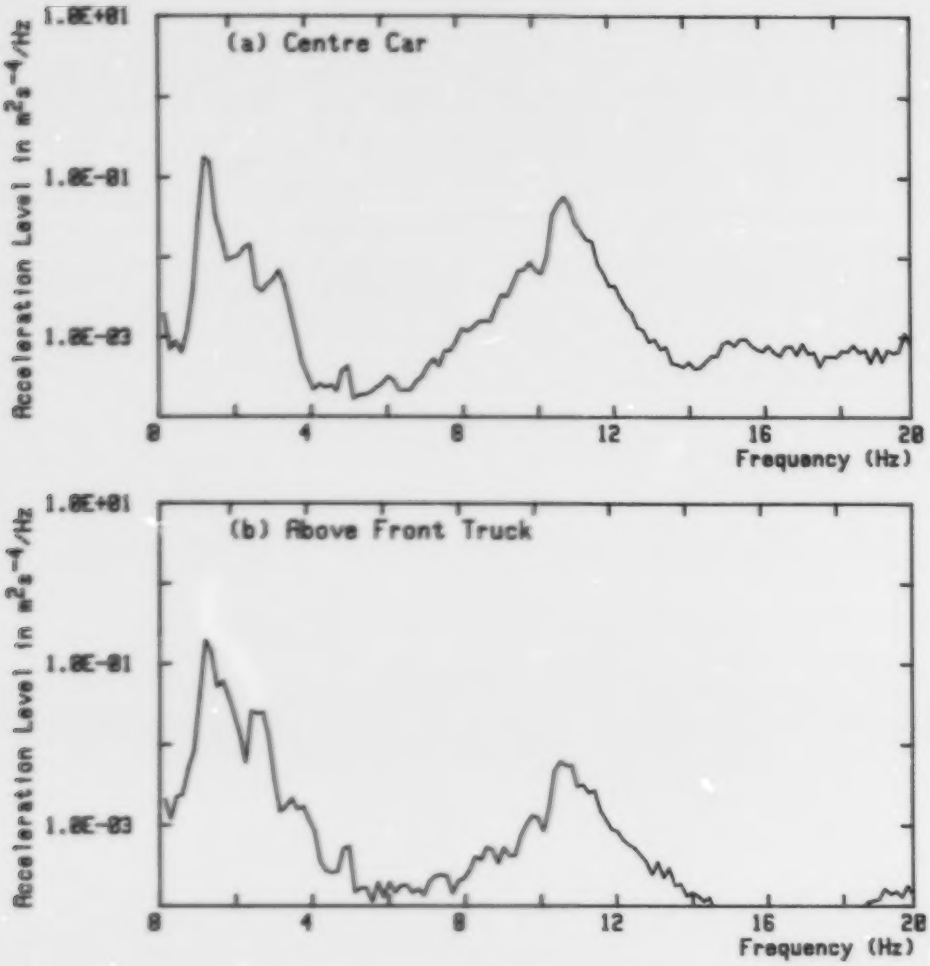


Figure 40/ Vertical Acceleration Spectra
ONR 'TEE' Car Fair Tangent

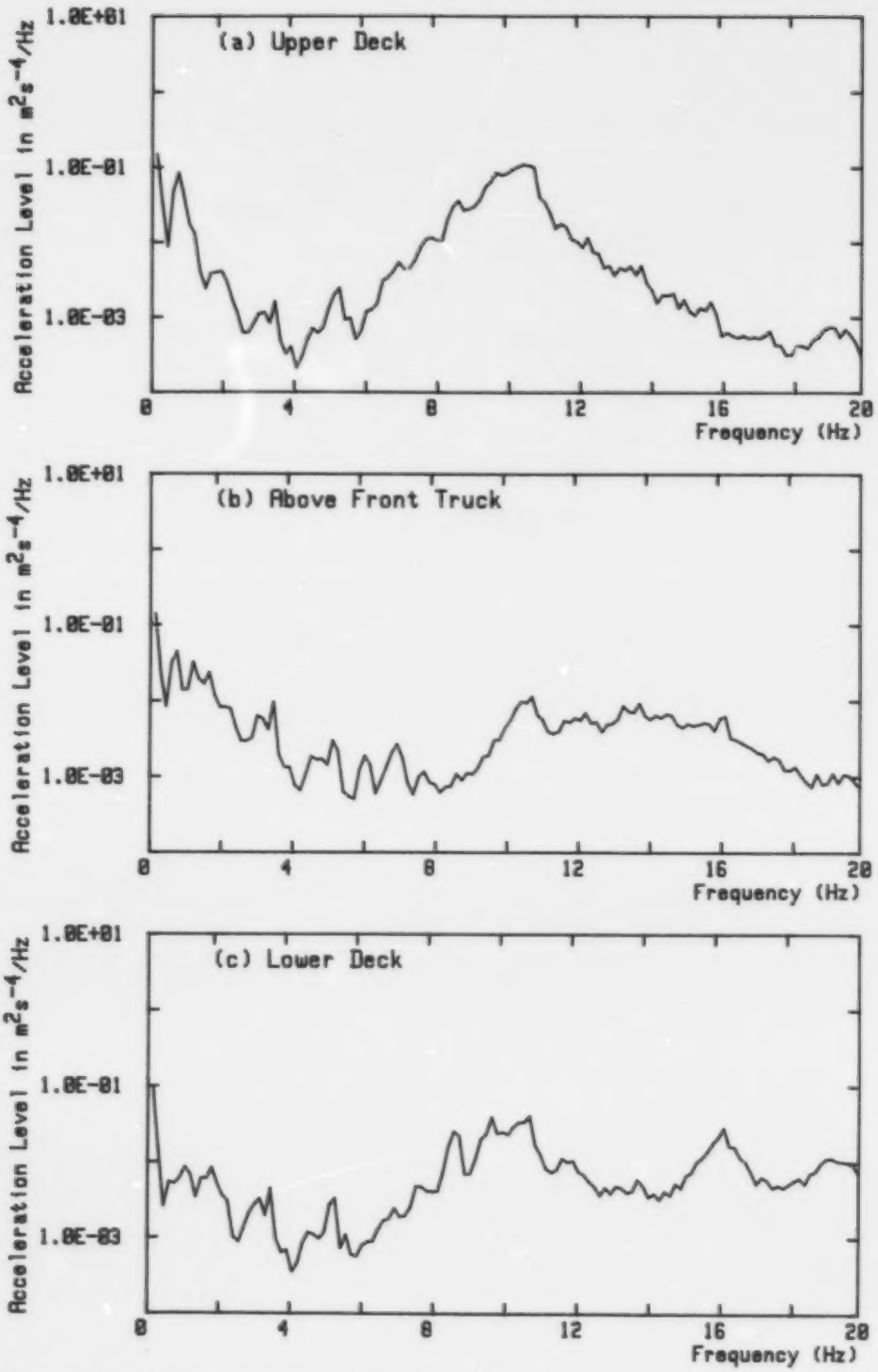


Figure 41/ Lateral Acceleration Spectra
Bi-Level Car Curved Track

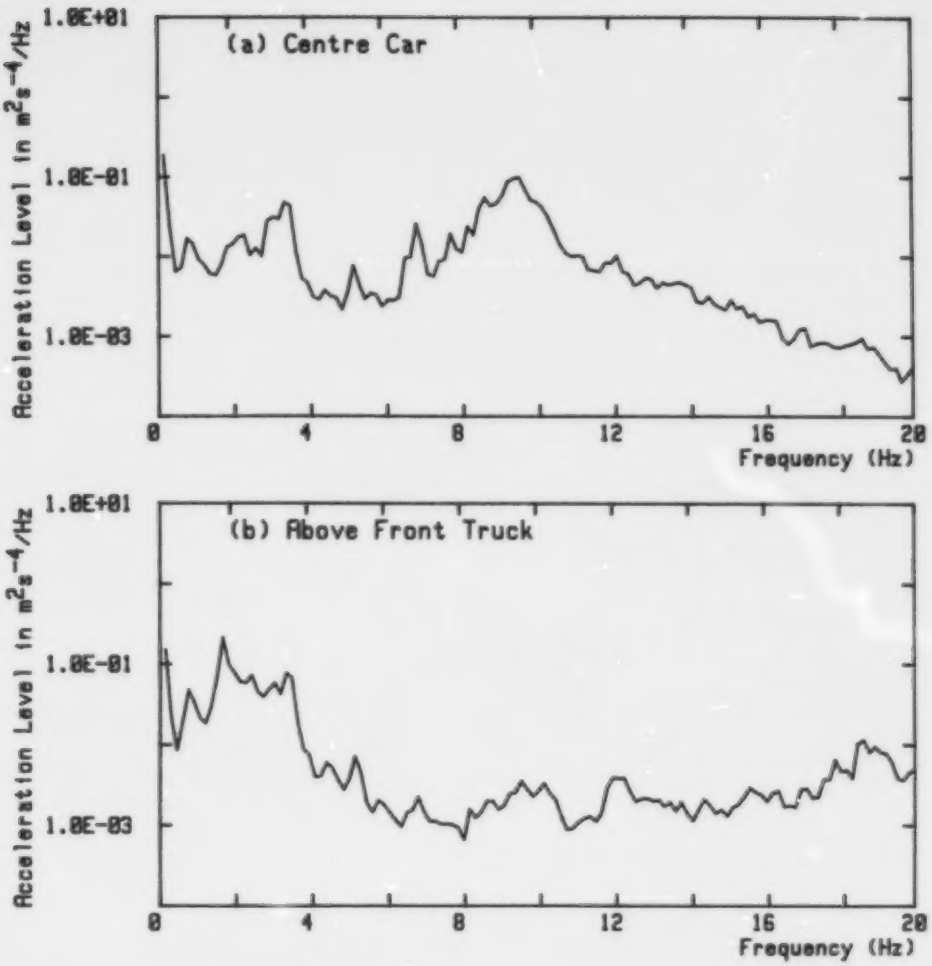


Figure 42/ Lateral Acceleration Spectra
Single-Level Car Curved Track

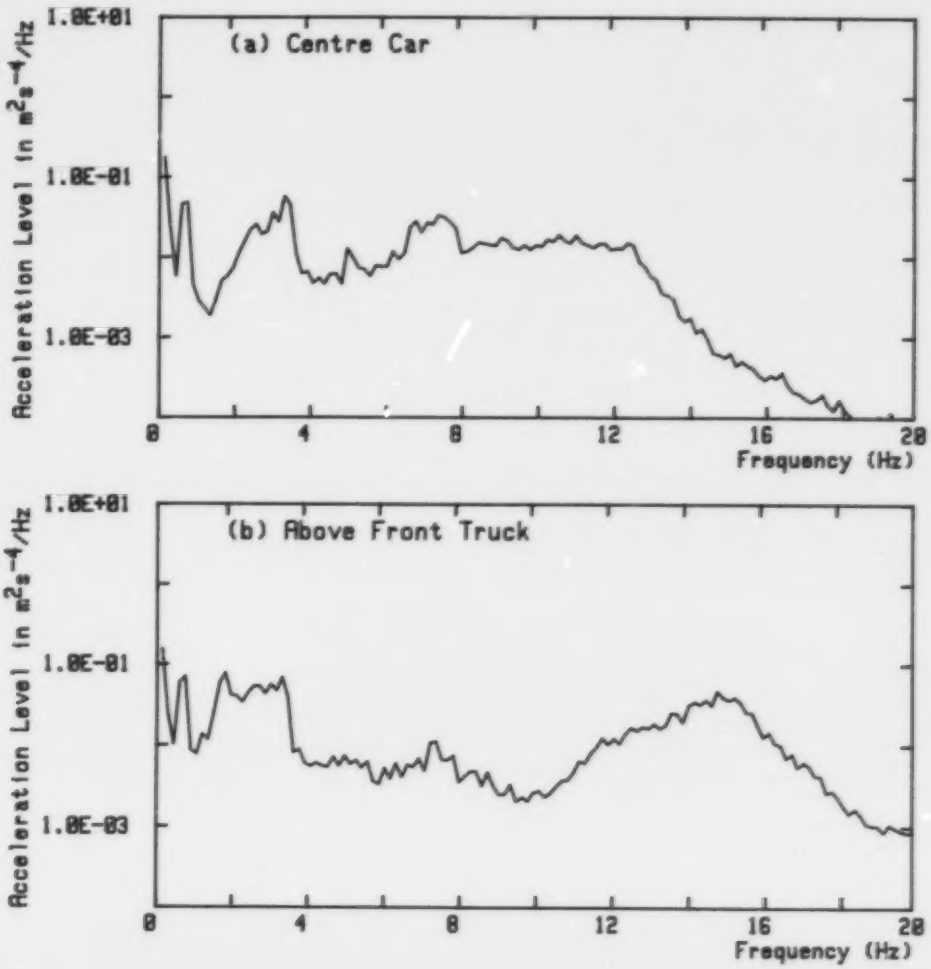


Figure 43/ Lateral Acceleration Spectra
ONR 'TEE' Car Curved Track

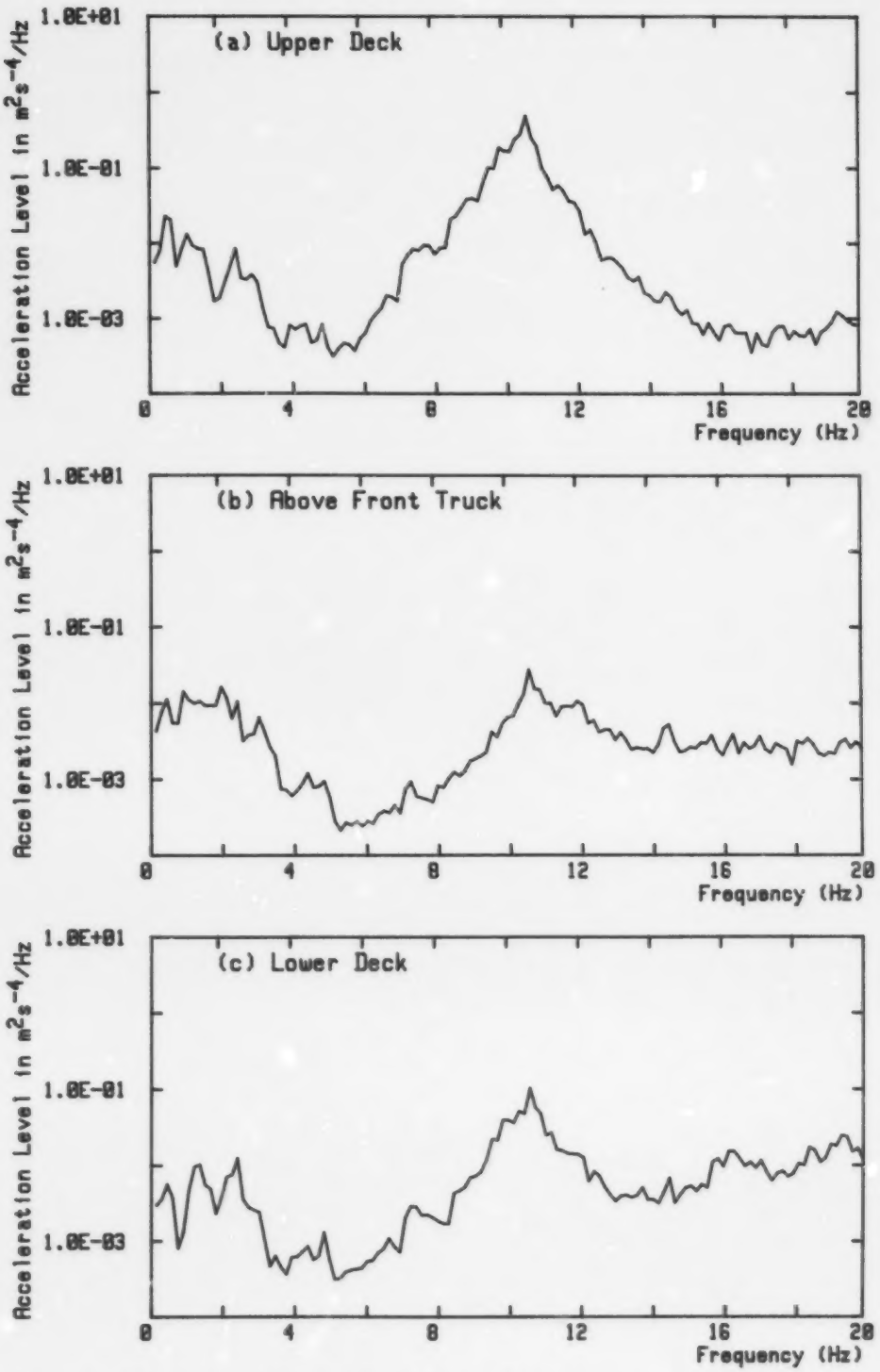


Figure 44/ Lateral Acceleration Spectra
Bi-Level Car Good Tangent

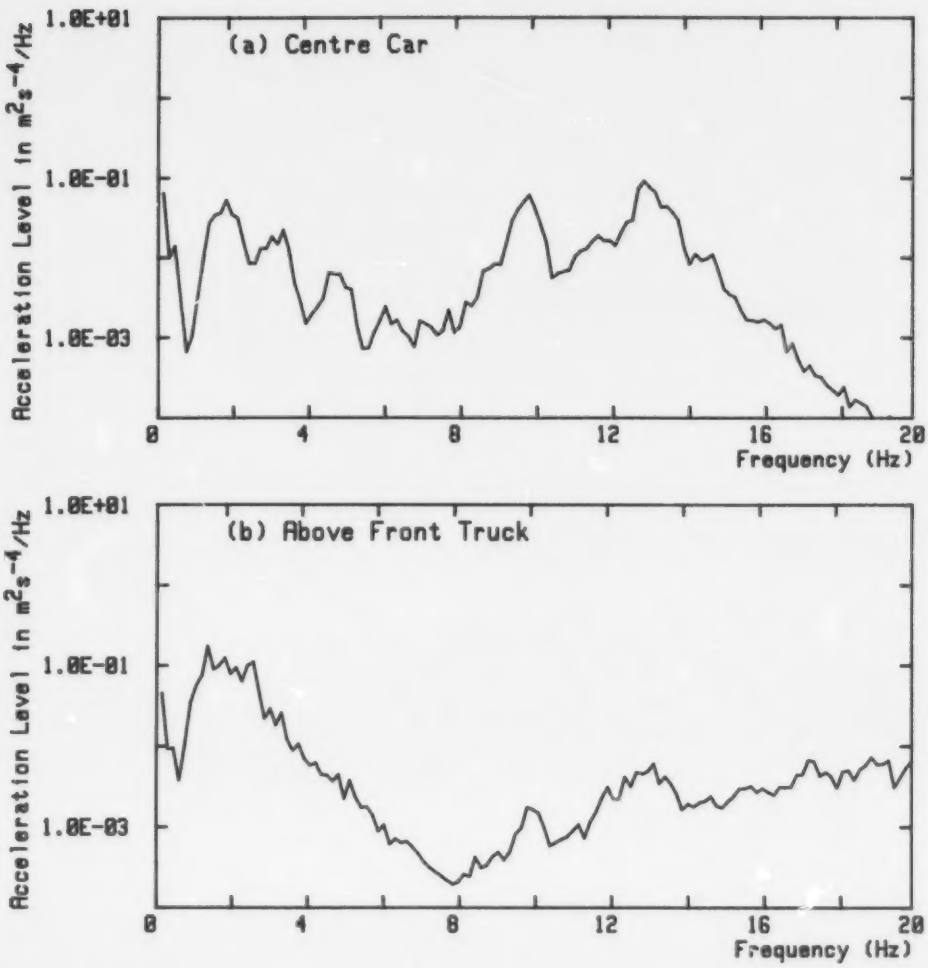


Figure 45/ Lateral Acceleration Spectra
Single-Level Car Good Tangent

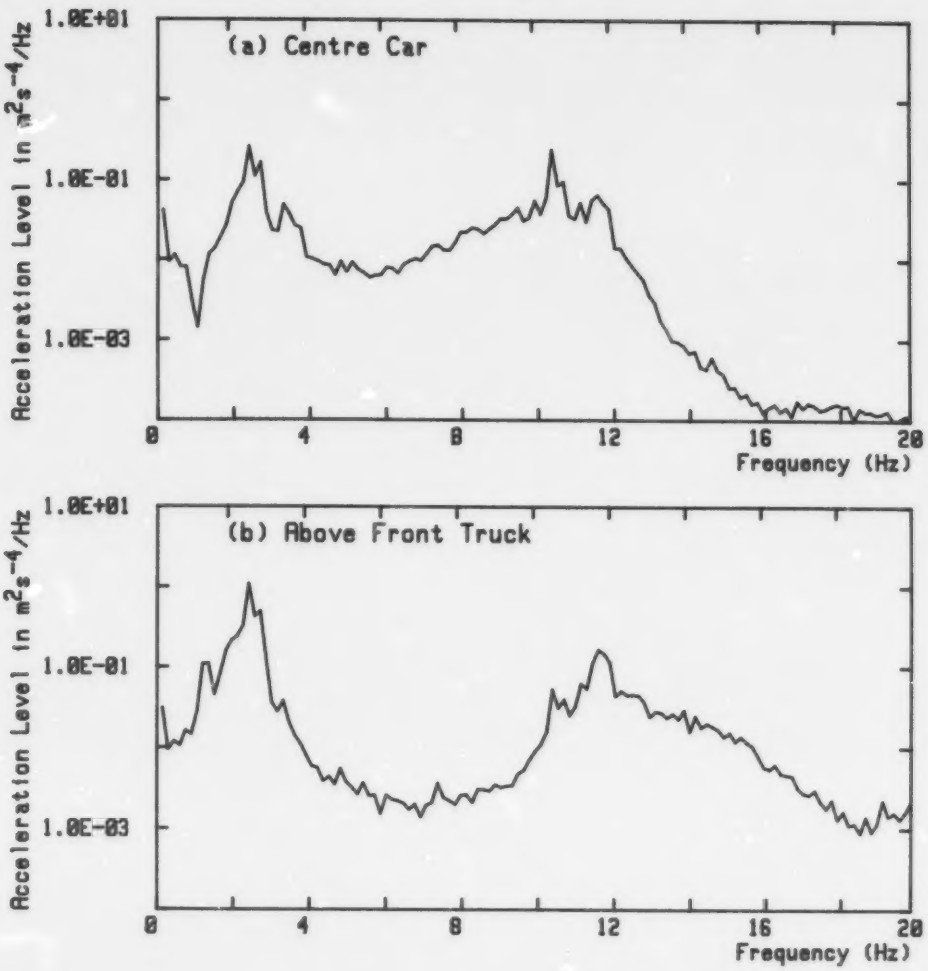


Figure 46/ Lateral Acceleration Spectra
ONR 'TEE' Car Good Tangent

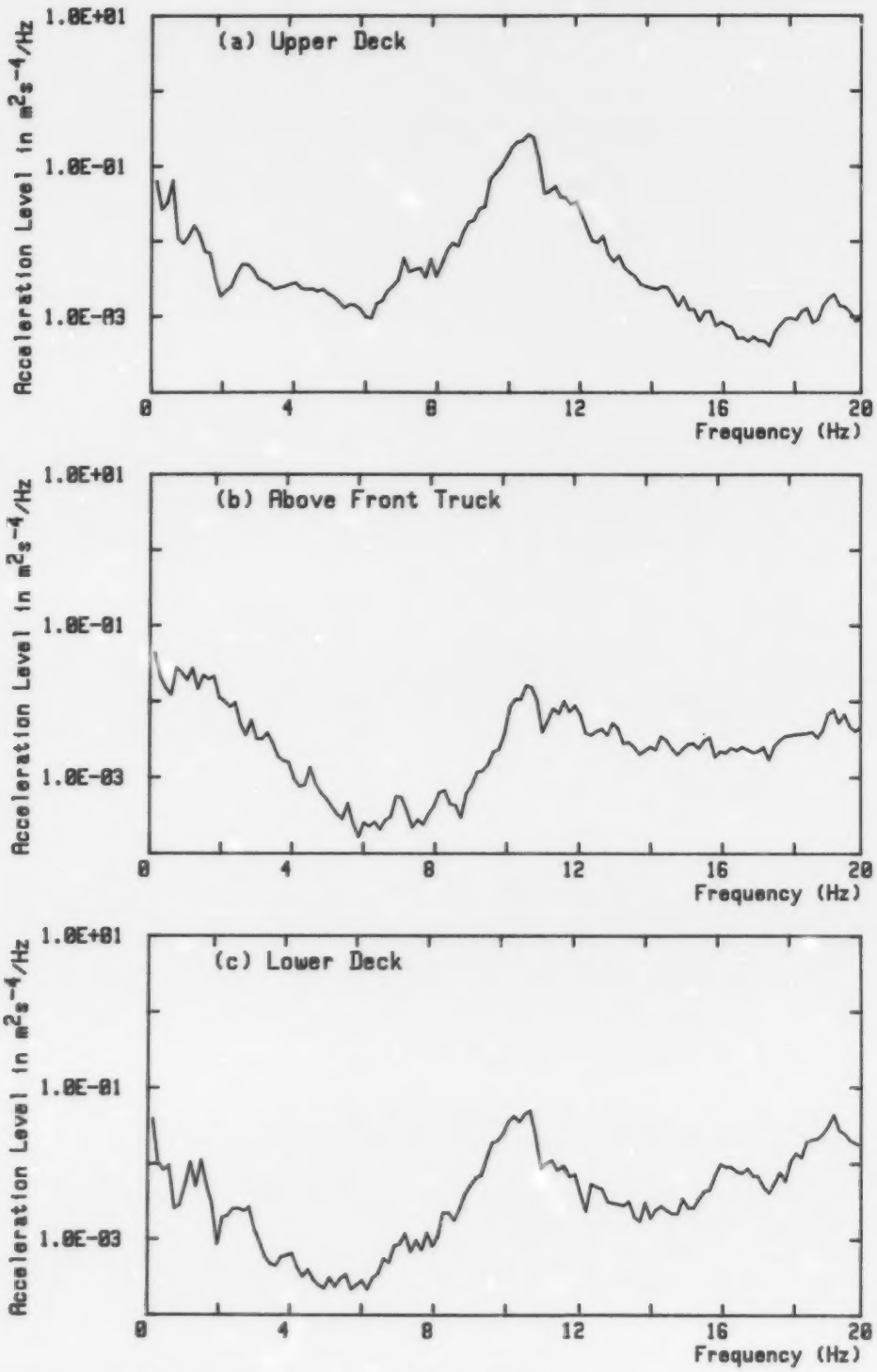


Figure 47/ Lateral Acceleration Spectra
Bi-Level Car Fair Tangent

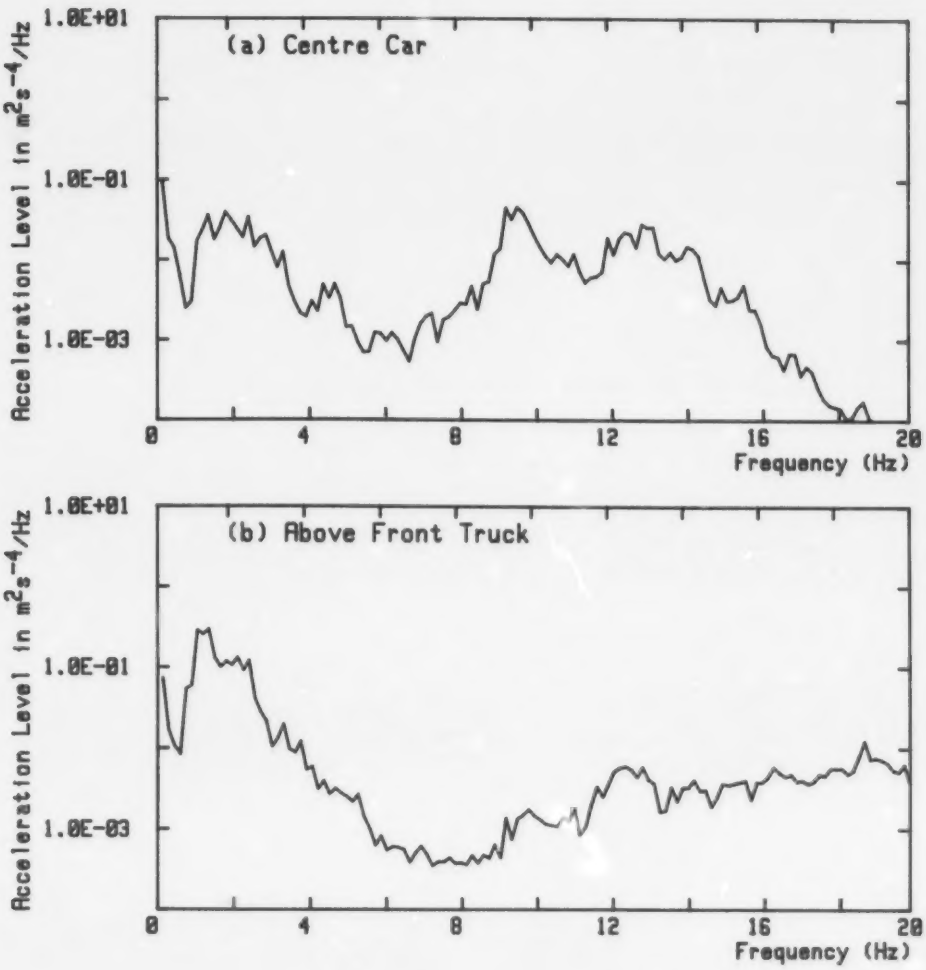


Figure 48/ Lateral Acceleration Spectra
Single-Level Car Fair Tangent

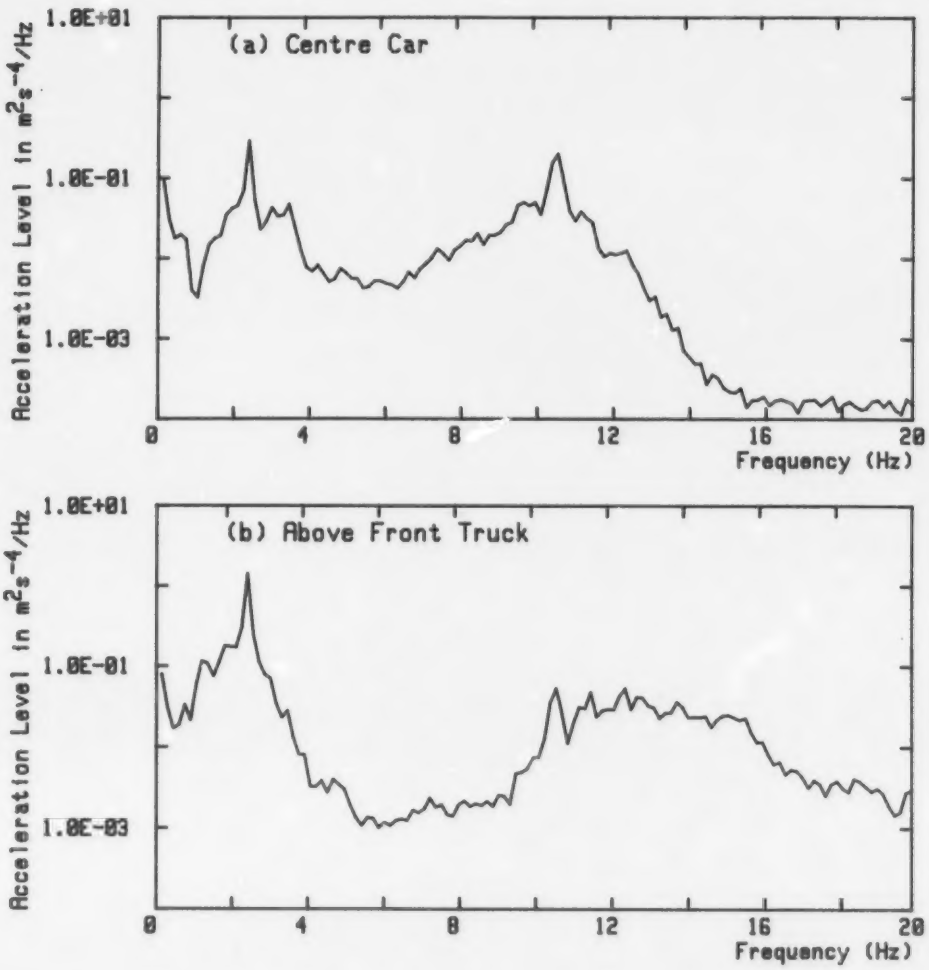


Figure 49/ Lateral Acceleration Spectra
ONR 'TEE' Car Fair Tangent

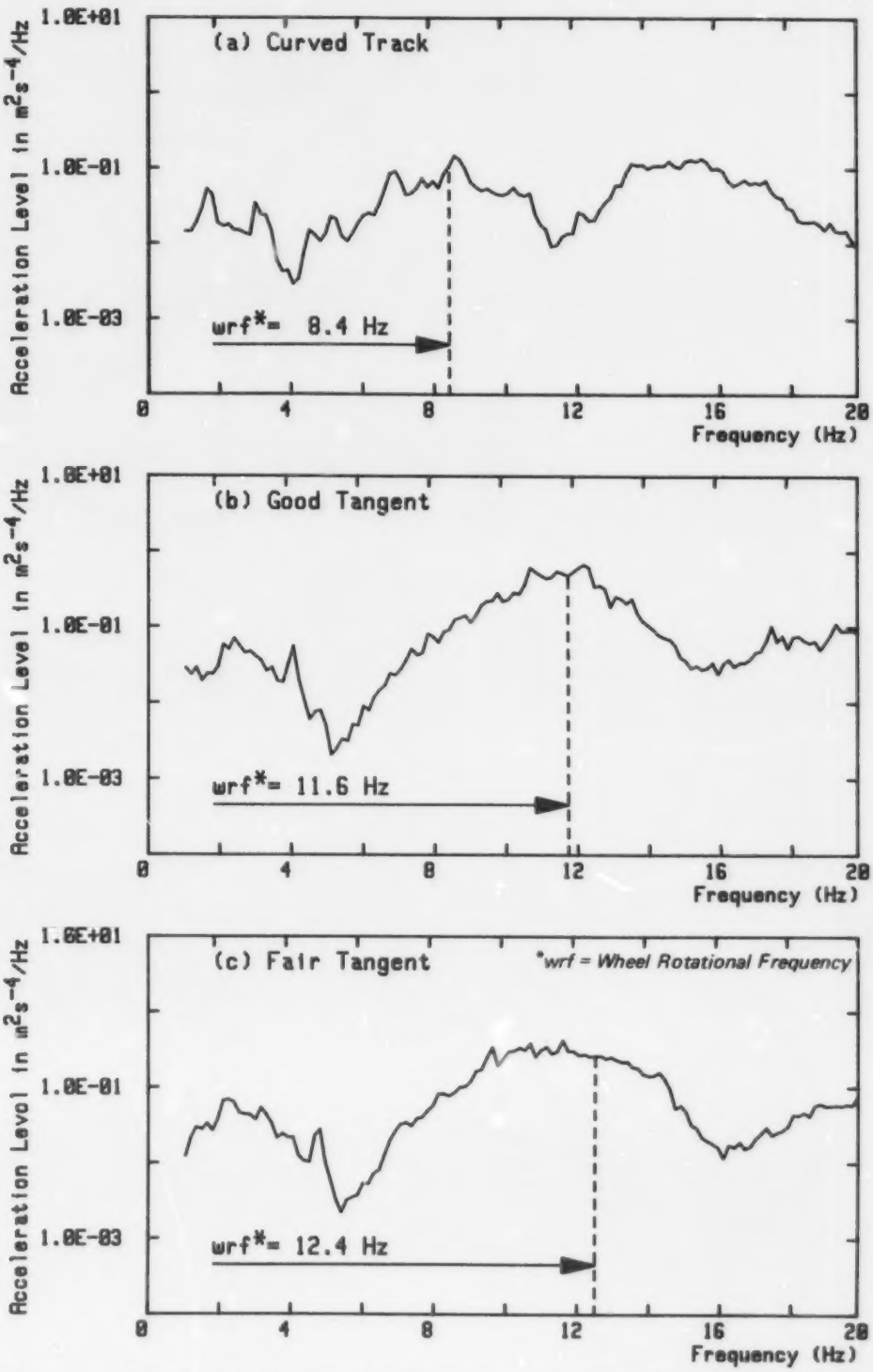


Figure 50/ Truck Vertical Acceleration Spectra
Bi-Level Car

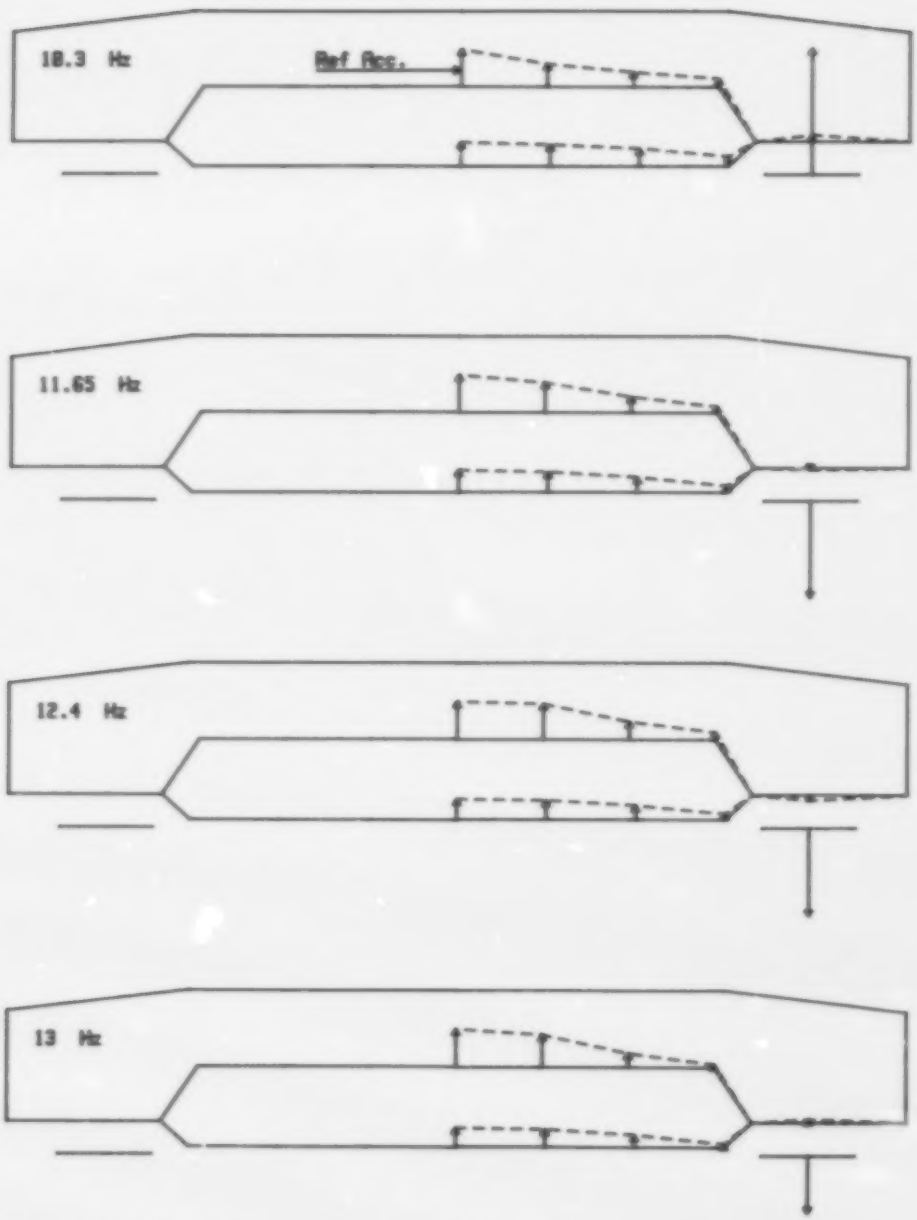


Figure 51/ Bi-Level Longitudinal Modeshapes

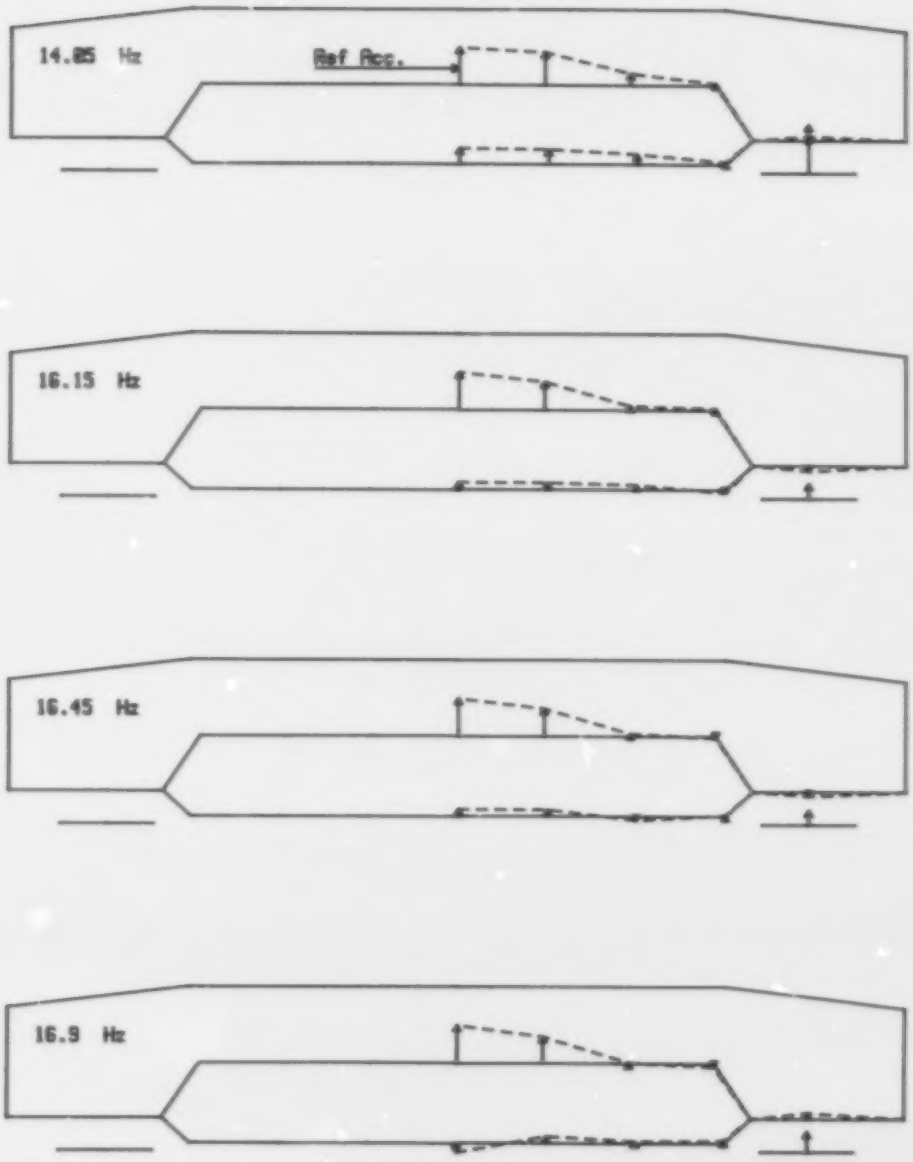


Figure 52/ Bi-Level Longitudinal Modeshapes

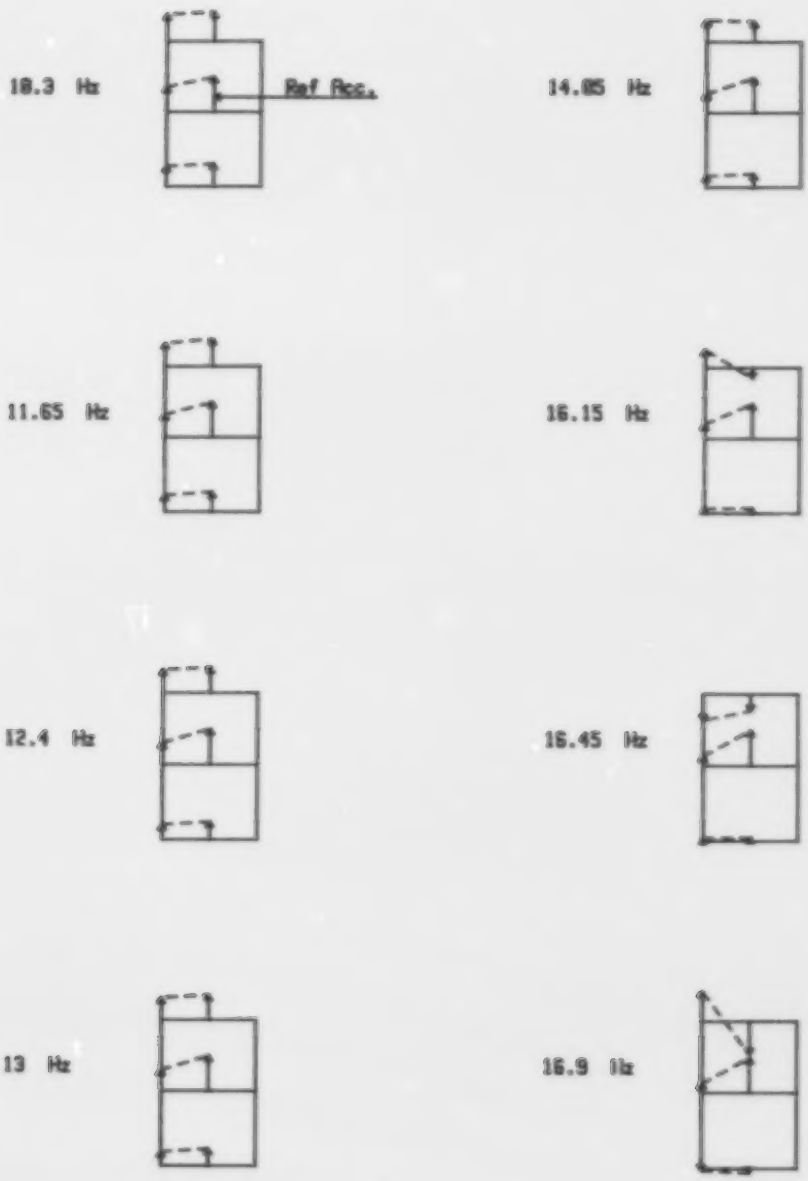
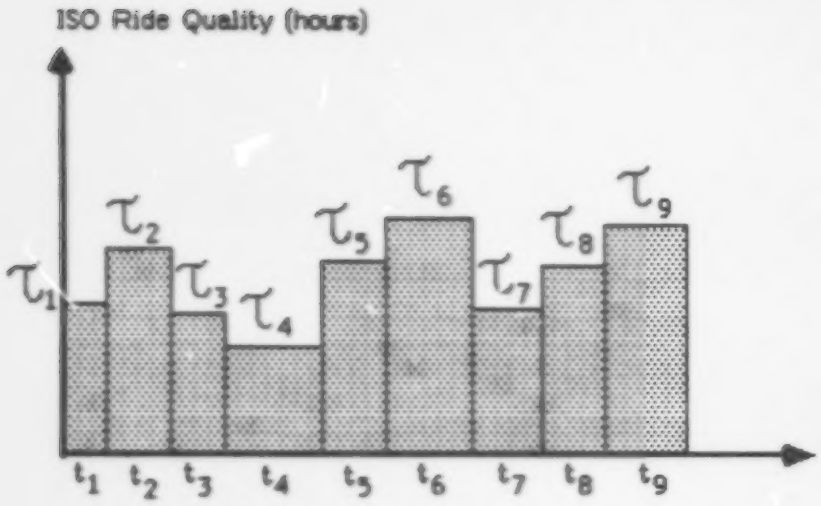


Figure 53/ Bi-Level Transverse Modeshapes

Typical Trip Ride Quality Profile



$$\text{Ride Acceptability Factor, RAF} = \frac{1}{\sum_i \left(\frac{t_i}{\tau_i}\right)}$$

If RAF >1 Acceptable
RAF <1 Unacceptable

Figure 54/ Definition of Ride Acceptability Factor

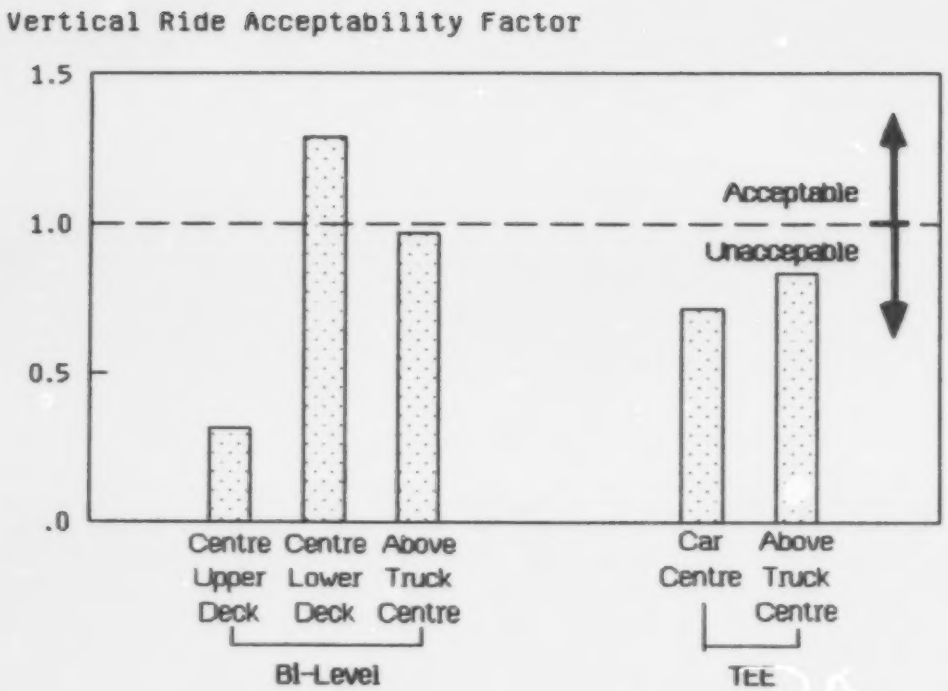


Figure 55/ ISO 2631 Vertical Ride Acceptability Factor for Toronto - Kapuskasing

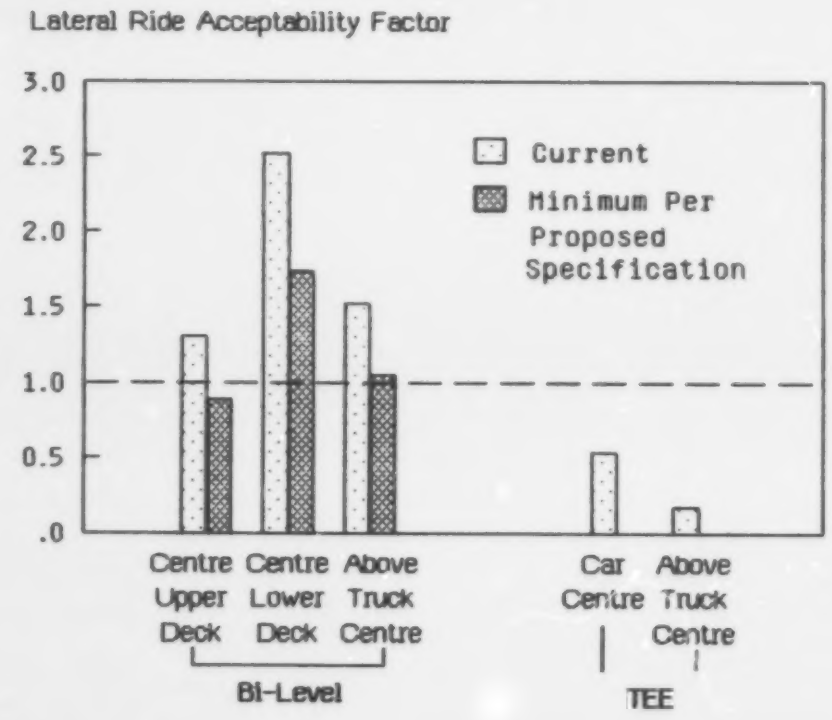


Figure 56/ ISO 2631 Lateral Ride Acceptability Factor for Toronto - Kapuskasing

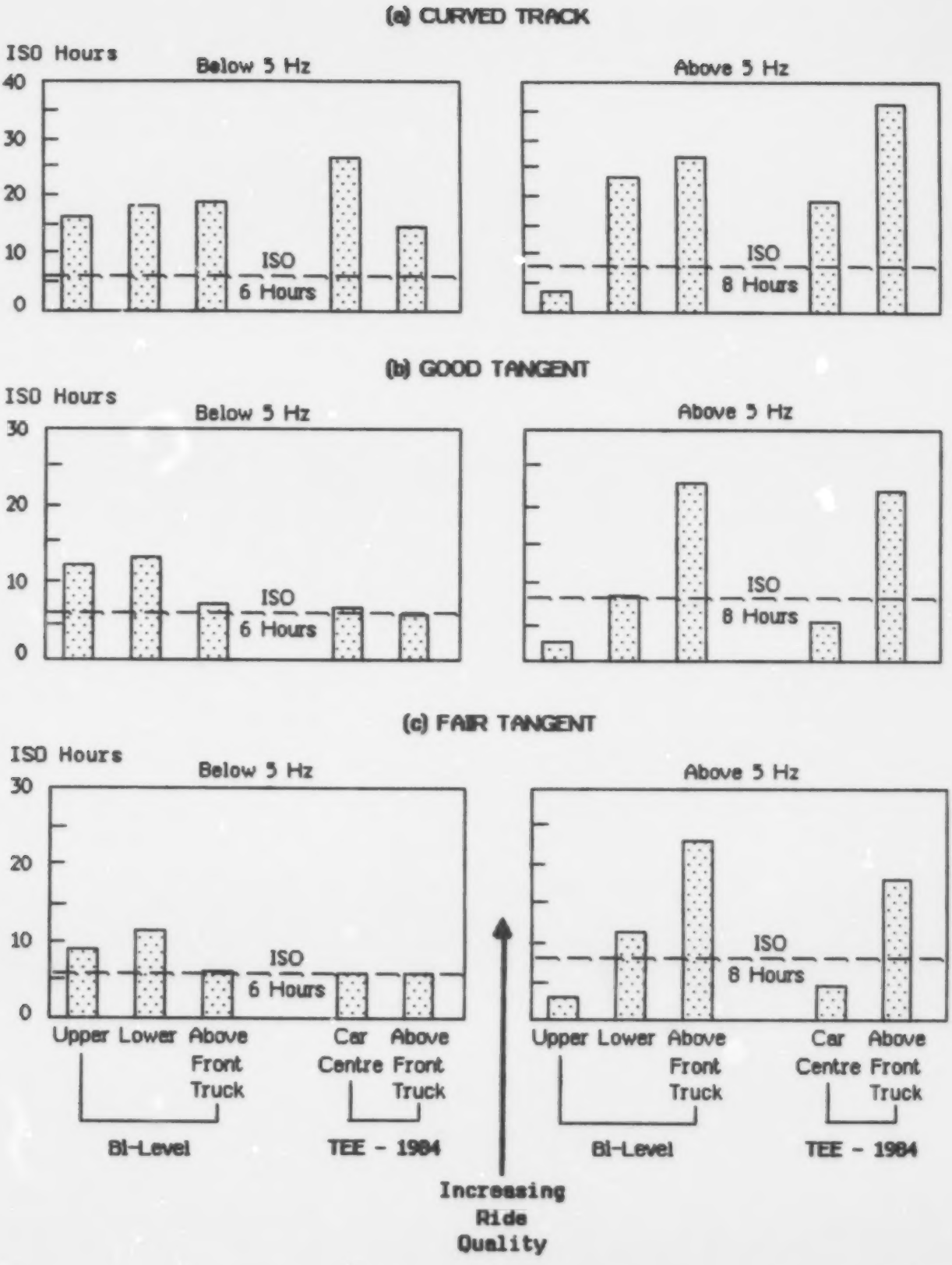


Figure 57/ ISO Vertical Ride Quality

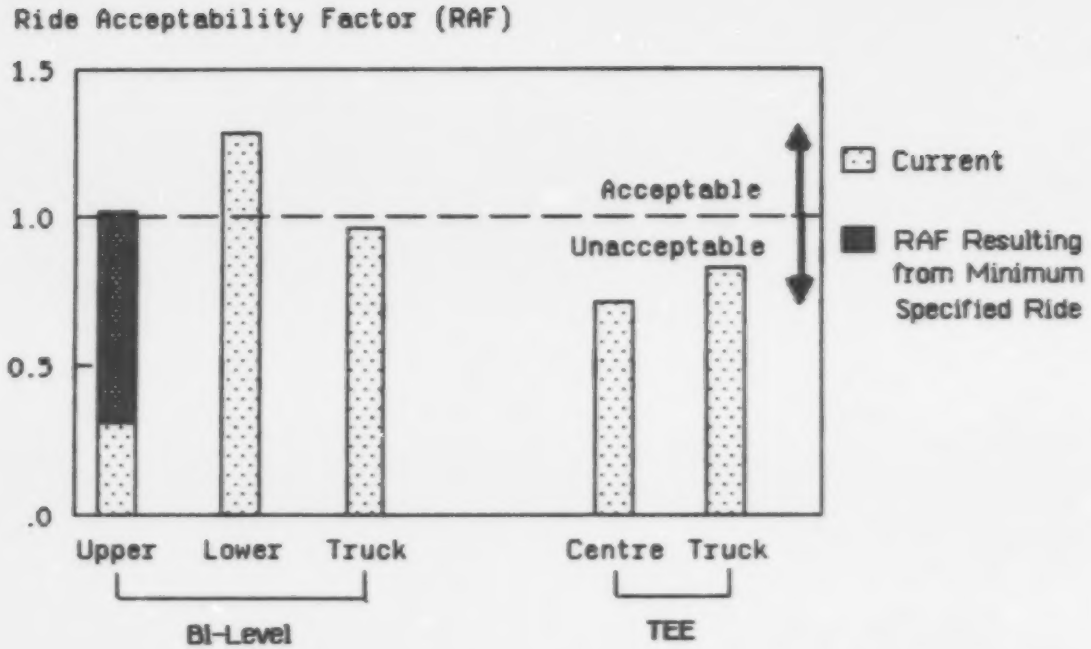


Figure 58/ Minimum Vertical Ride Acceptability (Per Ride Quality Specification)

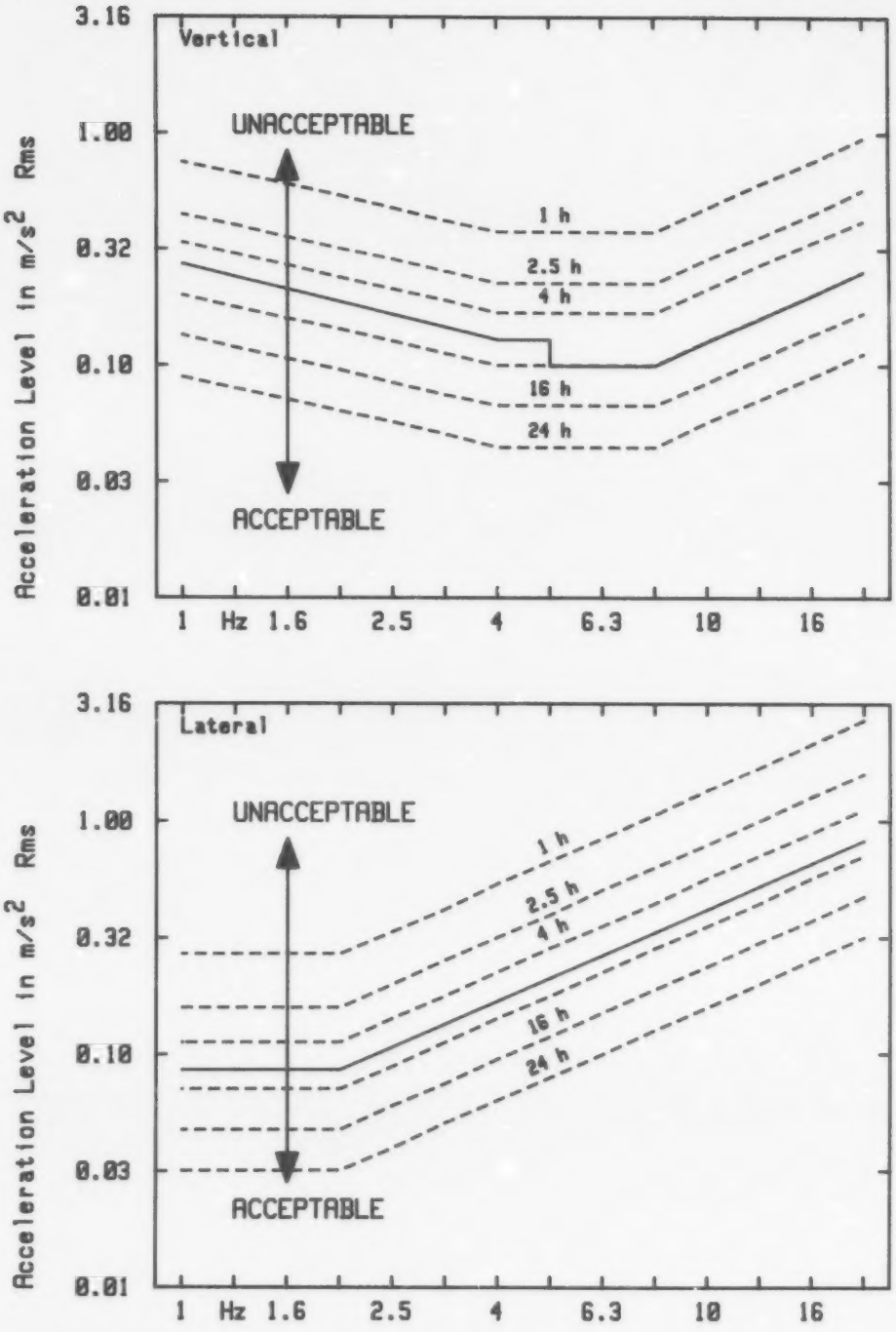


Figure 59/ Recommended ISO Ride Specification

Appendix A/ ONR Curved Track Characteristics from Mile Post 23 to 25

Mile Post (At centre of curve)	Degree of Curve (degrees and minutes)	Length of Circular Curve (feet)	Length of Spiral Curve (feet)	Following Length of Tangent (feet)	Height of Super-elevation (inches)
22.83	6 00 L	675	270	45	4
23.04	5 00 R	283	240	10	3.75
23.19	3 55 L	464	118	1021	3.25
23.55	6 10 R	449	185	980	4
23.92	1 02 R	579	170	1725	1
24.38	6 135 R	277	180	10	4
	6 04 L	500	180		
24.58	6 07 L	364	180	216	4.5
24.90	3 03 R	1171	180	962	2.5
25.25	1 00 R	597	60	703	2

Appendix B/ Vertical Ride Acceptability

Part I -- Analysis Per ISO 2631

Determine the Ride Acceptability Factor (RAF) for each of the car positions.

$$RAF = \tau'/T'$$

where $T' = \tau' \sum t_i/\tau_i$

therefore $RAF = (\sum_i t_i/\tau_i)^{-1}$

For the ONR track between North Bay and Kapuskasing, the following information has been supplied:

> Total track length is 523 km (325 mi) consisting of 60% tangent (20% good, 40% fair) and 40% curved track.

For the purpose of this analysis, it is necessary to evaluate the total track length from Toronto to Kapuskasing for which the breakdown of track into the same proportions of curved, good tangent and fair tangent as those above have been used. A total track length of 890 km (553 miles) has been used. See Tables 2 and 3 for a description of track distances and type. Assuming an average speed of 72.4 km/h (45 mph) on curved track and 104.6 km/h (65 mph) on tangent track, the t_i have been calculated for each track type as follows:

$t_1 = (890 \times 0.4)/72.4 = 4.92$ hours (curved track)
$t_2 = (890 \times 0.2)/104.6 = 1.70$ hours (good tangent)
$t_3 = (890 \times 0.4)/104.6 = 3.40$ hours (fair tangent)

(A) BI-LEVEL -- (1) Centre of Upper Deck

$\tau_1 = 3.7$
$\tau_2 = 2.5$
$\tau_3 = 3.0$

$$RAF = \left(\frac{4.92}{3.7} + \frac{1.70}{2.5} + \frac{3.40}{3.0}\right)^{-1} = 0.32 \text{ (Unacceptable)}$$

(ii) Centre of Lower Deck

$\tau_1 = 18.3$

$\tau_2 = 8.3$

$\tau_3 = 11.3$

$$RAF = \left(\frac{4.92}{18.3} + \frac{1.70}{8.3} + \frac{3.40}{11.3}\right)^{-1} = 1.29 \text{ (Acceptable)}$$

(iii) Above Truck Centre

$\tau_1 = 1.87$

$\tau_2 = 7.3$

$\tau_3 = 6.3$

$$RAF = \left(\frac{4.92}{18.7} + \frac{1.70}{7.3} + \frac{3.40}{6.3}\right)^{-1} = 0.97 \text{ (Acceptable within limits of analysis)}$$

(B) 1984 TEE -- (i) Deck Centre

$\tau_1 = 19.0$

$\tau_2 = 5.2$

$\tau_3 = 4.2$

$$RAF = \left(\frac{4.92}{19.0} + \frac{1.70}{5.2} + \frac{3.40}{4.2}\right)^{-1} = 0.72 \text{ (Unacceptable)}$$

(ii) Above Truck Centre

$\tau_1 = 14.7$

$\tau_2 = 5.7$

$\tau_3 = 6.0$

$$RAF = \left(\frac{4.92}{14.7} + \frac{1.70}{5.7} + \frac{3.40}{6.0}\right)^{-1} = 0.83 \text{ (Unacceptable)}$$

Part II -- At Minimum Specified Ride Quality

Assumptions:

1) The lowest ISO hour figure for bi-level vertical ride has changed to the minimum limit specified in the ride specification.
2) All other bi-level vertical ride figures at the same position have been changed by the same percentage as the lowest.

Re-evaluate RAF's

(A) BI-LEVEL -- (i) Centre of Upper Deck

Original	8 h ISO
$\tau_1 = 3.7$	11.8
$\tau_2 = 2.5$	8.0
$\tau_3 = 3.0$	9.6

Assume 2.5 is increased to 8 h ISO spec. and that τ_1 and τ_3 are increased by the same proportion (since all these τ_1 occur in the above 5 Hz range).

$$RAF = \left(\frac{4.92}{11.8} + \frac{1.70}{8.0} + \frac{3.40}{9.6}\right)^{-1} = 1.02 \quad \text{(Acceptable)}$$

The other two bi-level positions are acceptable.

APPENDIX C/ Lateral Ride Acceptability

Part I -- Analysis Per ISO 2631

Using the same interval times τ_1 to τ_3 as per vertical ride:

τ_1 = 4.92 h (curved)
τ_2 = 1.70 h (good tangent)
τ_3 = 3.40 h (fair tangent)
10.02 h (total trip time)

Using average τ^1 from test:

(A) BI-LEVEL (i) Upper Deck

τ_1 = 16.7
τ_2 = 8.7
τ_3 = 24.7

$$(RAF) = \left(\frac{4.92}{16.7} + \frac{1.70}{8.7} + \frac{3.40}{12.3}\right)^{-1} = 1.30 \text{ (Acceptable)}$$

(ii) Lower Deck

τ_1 = 26.0
τ_2 = 24.0
τ_3 = 24.7

$$RAF = \left(\frac{4.92}{26.0} + \frac{1.70}{24.0} + \frac{3.40}{24.7}\right)^{-1} = 2.51 \text{ (Acceptable)}$$

(iii) Truck Centre

τ_1 = 14.3
τ_2 = 19.0
τ_3 = 15.3

$$RAF = \left(\frac{4.92}{14.3} + \frac{1.70}{19.0} + \frac{3.40}{15.3}\right)^{-1} = 1.52 \text{ (Acceptable)}$$

(B) TEE-TRAIN (i) Deck Centre

$\tau_1 = 10.0$
$\tau_2 = 3.0$
$\tau_3 = 4.2$

$$RAF = \left(\frac{4.92}{10.0} + \frac{1.70}{3.0} + \frac{3.40}{4.2}\right)^{-1} = 0.54 \text{ (Unacceptable)}$$

(ii) Truck Centre

$\tau_1 = 6.8$
$\tau_2 = 1.0$
$\tau_3 = 1.1$

$$RAF = \left(\frac{4.92}{6.8} + \frac{1.70}{1.0} + \frac{3.40}{1.1}\right)^{-1} = 0.181 \text{ (Unacceptable)}$$

Part II -- At Minimum Specified Ride Quality

Assume worst ride quality figure (in ISO hours) deteriorates to the specified minimum (6 h) and all others reduced by the same percentage

$\tau_1 = 4.92$ h
$\tau_2 = 1.70$ h
$\tau_3 = 3.40$ h

(A) BI-LEVEL (i) Upper Deck

		$(\times \frac{6}{8.7})$
	Original	**6 h**
τ_1 =	16.7	11.5
τ_2 =	8.7	6.0
τ_3 =	12.3	8.5

$$6 \text{ h RAF} = \left(\frac{4.92}{11.5} + \frac{1.70}{6.0} + \frac{3.40}{8.5}\right)^{-1} = 0.90 \text{ (deemed acceptable)}$$

(ii) Lower Deck

τ_1 =	26.0	17.9
τ_2 =	24.0	16.6
τ_3 =	24.7	17.0

$$6 \text{ h RAF} = \left(\frac{4.92}{17.9} + \frac{1.70}{16.6} + \frac{3.40}{17.0}\right)^{-1} = 1.73 \text{ (acceptable)}$$

(iii) Truck Centre

	$(x \frac{6}{8.7})$
Original	**6 h**
$\tau_1 = 14.3$	9.9
$\tau_2 = 19.0$	13.1
$\tau_3 = 15.3$	10.6

$$6\text{ h RAF} = \left(\frac{4.92}{9.9} + \frac{1.70}{13.1} + \frac{3.40}{10.6}\right)^{-1} = 1.06 \text{ (acceptable)}$$